THIRD CANADIAN EDITION

ASTRO



SHOHINI GHOSE VESNA MILOSEVIC-ZDJELAR ARTHUR READ MICHAEL REID

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They want an overview of the course concepts that illustrates their value and impact in the world. They want resources that are easy to access, either portable print texts or mobile, accessible digital solutions. They want a resource that helps them study and is easy to review for assignments and exam preparation.

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A text that covers current trends and topics relevant to the students taking the course. A resource that helps them engage their students, whether in print or online, and that provides support for delivering and assessing course concepts.

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Delivers

An engaging experience, complete with print and digital solutions. Providing in-depth coverage of current trends, **ASTRO** is full of examples that detail how **astronomy** affects the world. Clear learning objectives, key terms, and chapter review cards help students study and prepare for course work. Easy-to-use online tools with activities, assignments, and quizzes support both formative and summative assessments, helping students learn by creating a more dynamic learning environment.

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YOUR BOOK



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ASTRO, Third Canadian Edition

by Shohini Ghose, Vesna Milosevic-Zdjelar, L. Arthur Read, and Michael Reid

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Production Service: MPS Limited

Copy Editor: Kelli Howey

Proofreader: MPS Limited

Indexer: Michael Ferreira

Design Director: Ken Phipps

Post-secondary Design PM: Pamela Johnston

Interior Design: Cenveo; Pamela Johnston

Cover Design: Courtney Hellam

Cover Image: Alan Dyer

Compositor: MPS Limited

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Adapted from *ASTRO*, Third Edition, by Michael A. Seeds and Dana Backman, published by Cengage Learning. Copyright © 2018 by Cengage Learning.

Printed and bound in Canada
1 2 3 4 23 22 21 20

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Library and Archives Canada Cataloguing in Publication

Title: ASTRO / Shohini Ghose, Vesna Milosevic-Zdjelar, L. Arthur Read, Michael Reid

Names: Ghose, Shohini, author. | Milosevic-Zdjelar, Vesna, 1961- author. | Read, L. Arthur, 1941- author. | Reid, Michael, author.

Description: Third Canadian edition. | Includes index.

Identifiers: Canadiana 20190206322 | ISBN 9780176857059 (softcover)

Subjects: LCSH: Astronomy—Textbooks. | LCGFT: Textbooks.

Classification: LCC QB61 .G56 2020 | DDC 520—dc23

ISBN-13: 978-0-17-685705-9
ISBN-10: 0-17-685705-2

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BRIEF CONTENTS

PART 1 Exploring the Sky 2

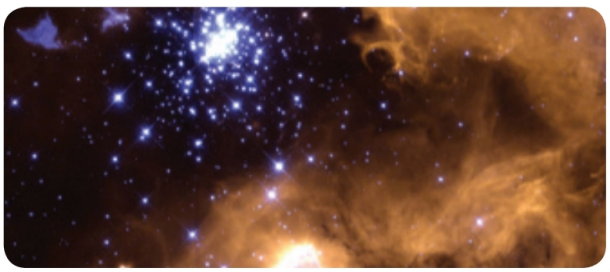
1 The Scale of the Cosmos: Space and Time 2
2 User's Guide to the Sky: Patterns and Cycles 16
3 The Origin of Modern Astronomy 44
4 Astronomical Telescopes and Instruments: Extending Humanity's Vision 72



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PART 2 The Stars 92

5 The Sun: The Closest Star 92
6 The Family of Stars 120
7 The Structure and Formation of Stars 144
8 The Deaths of Stars 168



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PART 3 Galaxies and Cosmology 198

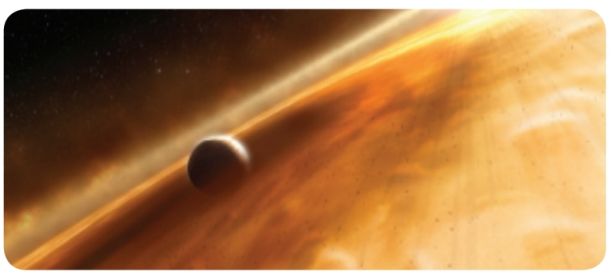
9 The Milky Way Galaxy 198
10 Galaxies 222
11 Cosmology in the 21st Century 250



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PART 4 The Solar System 276

12 Planet Formation and Exoplanets 276
13 Comparative Planetology of the Terrestrial Planets 304
14 The Outer Solar System 334



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PART 5 Life 356

15 Life on Other Worlds 356
Afterword 376
Appendix A: Units and Astronomical Data 378
Appendix B: Observing the Sky 384
Appendix C: Celestial Profiles 387
Index 392



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CONTENTS

PART 1 Exploring the Sky 2

1 The Scale of the Cosmos: Space and Time 2

1.1 Astronomy: A Global Human Adventure 4
1.2 From Solar System to Galaxy to Universe 6
Visualizing Astronomy 1.1 The Scale of the Very Small and Very Large: Powers of 10 8
1.3 The Cosmic Calendar: Concepts of Time 12
The Big Picture 13
Review and Discussion Questions 14
Global Story of Astronomy: Collection and Analysis of Data from Juno 15

2 User's Guide to the Sky: Patterns and Cycles 16

2.1 The Stars 18
Constellations 18
The Names of Stars 19
The Brightness of Stars 19
2.2 The Sky and Its Motions 21
The Celestial Sphere 21
Visualizing Astronomy 2.1 The Sky Around Us 22
Precession 24
2.3 The Cycle of the Sun 25
The Annual Motion of the Sun 25
The Seasons 26
2.4 The Cycles of the Moon 27
The Motion of the Moon 27
The Cycle of Moon Phases 27
Visualizing Astronomy 2.2 The Cycle of the Seasons 28
Visualizing Astronomy 2.3 The Phases of the Moon 30
2.5 Eclipses 32
Solar Eclipses 32
Lunar Eclipses 33
2.6 Stellar Coordinates 36
2.7 Timekeeping 36
Timekeeping by Day 36
Timekeeping by Month 37
Timekeeping by Year 37
What Time Is It? 37
Calendars 37
2.8 Night Sky Tours 38
The Big Picture 42
Review and Discussion Questions 43

3 The Origin of Modern Astronomy 44

3.1 The Birth of Astronomy 46
The Geocentric Model of the Universe 49
Visualizing Astronomy 3.1 The Ancient Universe 52
3.2 A Revolutionary Idea 54
The Heliocentric Model 54
3.3 Observing the Patterns of Planetary Motion 56
Kepler's Three Laws of Planetary Motion 57
3.4 A New Window on the Universe 59
Telescopic Observations 59
3.5 The Science of Motion 62
The Universal Theory of Gravitation 63
Orbital Motion 64
Tides: Gravity in Action 65
Visualizing Astronomy 3.2 Orbiting Earth 66
Universal Motion 68
The Big Picture 69
Review and Discussion Questions 69
Global Story of Astronomy: Earthrise 2017 71

4 Astronomical Telescopes and Instruments: Extending Humanity's Vision 72

4.1 Radiation: Information from Space 74
Light as a Wave and as a Particle 74
The Electromagnetic Spectrum 75
4.2 Telescopes 76
Two Kinds of Telescopes 76
The Powers of a Telescope 78
4.3 Observatories on Earth: Optical and Radio 80
Visualizing Astronomy 4.1 Modern Astronomical Telescopes 82
4.4 Astronomical Instruments and Techniques 84
Imaging Systems and Photometers 84
Spectrographs 85
4.5 Airborne and Space Observatories 86
The Ends of the Visual Spectrum 86
Telescopes in Space 87
The Big Picture 90
Review and Discussion Questions 90

PART 2 The Stars 92

5 The Sun: The Closest Star 92

5.1 The Sun: Basic Characteristics 94
Distance and Size 94
Mass and Density 95

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5.2 Properties of Blackbody Radiation 95
Atoms and Subatomic Particles 95
Temperature, Heat, and Blackbody Radiation 96
5.3 The Sun's Surface 97
The Photosphere 97
Heat Flow in the Sun 98
5.4 Light, Matter, and Motion 99
Electron Shells 99
Excitation of Atoms 100
The Doppler Effect 101
5.5 The Sun's Atmosphere 103
Formation of Spectra 103
The Sun's Chemical Composition 103
Visualizing Astronomy 5.1 Atomic Spectra 104
The Chromosphere 106
The Corona 108
5.6 Solar Activity 110
Observing the Sun 110
Sunspots 110
Insight into the Sun's Interior 111
The Sun's Magnetic Cycle 111
Visualizing Astronomy 5.2 Sunspots and the Sunspot Cycle 112
Chromospheric and Coronal Activity 114
Visualizing Astronomy 5.3 Magnetic Solar Phenomena 116
The Big Picture 118
Review and Discussion Questions 119

6 The Family of Stars 120
6.1 Star Distances 122
The Surveyor's Triangulation Method 122
The Astronomer's Triangulation Method 122
6.2 Apparent Brightness, Intrinsic Brightness, and Luminosity 124
Brightness and Distance 124
Absolute Visual Magnitude 124
Luminosity 125
6.3 Star Temperatures 125
Temperature Spectral Classification 126
6.4 Star Sizes 129
Luminosity, Temperature, and Diameter 129
Luminosity Spectral Classification 131
6.5 Star Masses: Binary Stars 132
Binary Stars in General 132
Three Kinds of Binary Systems 133
6.6 Typical Stars 136
Luminosity, Mass, and Density 137
Visualizing Astronomy 6.1 The Family of Stars 138
Surveying the Stars 140
The Big Picture 141
Review and Discussion Questions 142
Global Story of Astronomy: ESO's 50th Anniversary photo of Thor's Helmet 143

7 The Structure and Formation of Stars 144
7.1 Models of Stellar Structure 146
The Laws of Conservation of Mass and Energy 146
Energy Transport 147
Hydrostatic Equilibrium 148
A Complete Stellar Model 148
7.2 Nuclear Fusion in the Sun and Stars 150
Nuclear Binding Energy 150
Hydrogen Fusion 151
Neutrinos from the Sun's Core 152
The Pressure–Temperature Thermostat 154
7.3 Main-Sequence Stars 154
The Mass–Luminosity Relation 154
Brown Dwarfs 154
The Life of a Main-Sequence Star 155
7.4 The Birth of Stars 156
The Interstellar Medium 157
Visualizing Astronomy 7.1 Three Kinds of Nebulae 158
The Formation of Stars from the Interstellar Medium 160
The Formation of Protostars 162
Observations of Star Formation 163
The Orion Nebula 163
Visualizing Astronomy 7.2 Star Formation in the Orion Nebula 164
Evidence of Young Stars 166
The Big Picture 166
Review and Discussion Questions 167

8 The Deaths of Stars 168
8.1 The Beginning of the End 170
Red Dwarf Stars 170
Sunlike Stars 170
Expansion into a Giant 171
Helium Fusion 171
Star Clusters: Evidence of Evolution 173
8.2 The Final End of a Low-Mass Star 173
Planetary Nebulae 173
Visualizing Astronomy 8.1 Star Cluster H–R Diagrams 174
White Dwarfs 176
The Fate of the Sun and the End of Earth 177
8.3 The Evolution of Binary Systems 178
Mass Transfer and Accretion Disks 178
Novae 179
Type Ia Supernova: Thermonuclear or White Dwarf Supernova 180
8.4 The Deaths of Massive Stars 180
Nuclear Fusion in Massive Stars 180
Supernova Explosions of Massive Stars 181
Types of Supernovae 182
Observations of Supernovae 183
8.5 Neutron Stars 185
Theoretical Prediction of Neutron Stars 186
The Discovery of Pulsars 186
The Evolution of Pulsars and Neutron Stars 187
8.6 Black Holes and Relativity 188
Escape Velocity 188
Special Relativity and Space-Time 188
Schwarzschild Black Holes 190
Leaping into a Black Hole 191
The Search for Black Holes 192
Energy from Compact Objects: Jets 193
Energy from Compact Objects: Gamma-Ray Bursts 193
Taking a Picture of a Black Hole 194
8.7 Gravitational Waves 195
The Big Picture 196
Review and Discussion Questions 196

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PART 3 Galaxies and Cosmology 198

9 The Milky Way Galaxy 198

9.1 The Discovery of the Galaxy 200
The Great Star System 201
The Size of the Milky Way 202
Star Clusters and the Centre of the Galaxy 203
Components of the Galaxy 205
The Mass of the Galaxy and the Dark Matter 206

9.2 Spiral Arms and Star Formation 209
Tracing the Spiral Arms 209
Star Formation in Spiral Arms 210

9.3 The Origin and History of the Milky Way 212
The Age of the Milky Way 212
Stellar Populations 212
The Element-Building Cycle 213
The History of the Milky Way Galaxy 214

Visualizing Astronomy 9.1 Sagittarius A* 216

9.4 The Nucleus 218
Observations of the Galactic Nucleus 219

The Big Picture 219

Review and Discussion Questions 220

Global Story of Astronomy: Comet 67P/Churyumov-Gerasimenko and the *Rosetta* spacecraft 221

10 Galaxies 222

10.1 The Family of Galaxies 224

Visualizing Astronomy 10.1 Galaxy Classification 226

10.2 The Distribution of Galaxies in the Universe 228
Distance Ladder 228
The Hubble Law 231
Telescopes as Time Machines 231
Organization of Galaxies in the Universe 232

10.3 The Masses of Galaxies and Dark Matter 233
Measuring Masses of Galaxies 233
Dark Matter in Galaxies and Clusters of Galaxies 234

10.4 The Evolution of Galaxies 237
Colliding Galaxies 237

10.5 Active Galaxies, Quasars, and Supermassive Black Holes 241
Active Galaxies 241
Quasars 245
The Search for a Unified Model 247

The Big Picture 248

Review and Discussion Questions 248

11 Cosmology in the 21st Century 250

11.1 Introduction to the Universe 252
The Edge–Centre Problem 252
The Necessity of a Beginning 252
Cosmic Expansion 253

11.2 The Big Bang Theory 254
Necessity of the Big Bang 254
Evidence for the Big Bang: The Cosmic Microwave Background 254
Particles and Nucleosynthesis: The First Seconds and Minutes 257

Visualizing Astronomy 11.1 The Large Hadron Collider 258
Recombination and Reionization: The First Thousands and Millions of Years 260

11.3 Space and Time, Matter and Energy 262
Looking at the Universe 262
The Cosmic Redshift 263
Model Universes 263
Dark Matter in Cosmology 264

11.4 Modern Cosmology 265
Inflation 265
The Acceleration of the Universe 267
Dark Energy and Acceleration 267
The Fate of the Universe 269
A New Way to Observe the Universe 269
The Origin of Structure 271
CMB Irregularities and the Curvature of Space-Time 272

The Big Picture 274

Review and Discussion Questions 274

Global Story of Astronomy: Burcin's Galaxy 275

PART 4 The Solar System 276

12 Planet Formation and Exoplanets 276

12.1 The Great Chain of Origins 278
The History of the Atoms in Your Body 278
The Origin of the Solar System 278

12.2 A Survey of the Planets 279
Revolution and Rotation 279
Two Kinds of Planets 280

12.3 Space Debris: Asteroids, Comets, and Meteoroids 280
Asteroids 280
Comets 281

Visualizing Astronomy 12.1 Terrestrial and Jovian Planets 282
Meteoroids, Meteors, Meteorites 285

12.4 The Story of Planet Formation 287
The Age of the Solar System 287
Chemical Composition of the Solar Nebula 289
Condensation of Solids 289
Formation of Planetesimals 290
Growth of Protoplanets 290
Bombardment of the Planets 292
Explaining the Characteristics of the Solar System 293

12.5 Planet-Forming Disks Around Young Stars 295

12.6 Exoplanets: Planets Orbiting Other Stars 297

The Big Picture 302

Review and Discussion Questions 302

13 Comparative Planetology of the Terrestrial Planets 304

13.1 A Travel Guide to the Terrestrial Planets 306
The Scale of the Solar System 306
Revolution and Rotation 306

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Two Kinds of Planets 306
Core, Mantle, and Crust 306
Atmospheres 307

13.2 Earth: The Active Planet 308
Earth's Interior 308
Earth's Active Crust 309
Earth's Atmosphere 309

Visualizing Astronomy 13.1 The Active Earth 310
Oxygen in Earth's Atmosphere 312
A Short Geological History of Earth 313

13.3 The Moon 314
Lunar Geology 314
The Origin of Earth's Moon 314
The History of Earth's Moon 315
Exploration 316

13.4 Mercury 318
A History of Mercury 318
Exploration 318

13.5 Venus 319
The Atmosphere of Venus 320
The Surface of Venus 320
The History of Venus 321
Exploration 322

13.6 Mars 322
The Atmosphere of Mars 322
Exploring the Surface of Mars 323
Searching for Water on Mars 324
A History of Mars 327

Visualizing Astronomy 13.2 When Good Planets Go Bad 328
Exploration 330
The Moons of Mars 330

The Big Picture 331

Review and Discussion Questions 332

14 The Outer Solar System 334

14.1 Exploring the Outer Planets 336
Physical Characteristics 337

14.2 Jupiter 337
Jupiter's Rings 338
Jupiter's Family of Moons 339

Visualizing Astronomy 14.1 Jupiter's Atmosphere, Magnetosphere, and Rings 340
Exploration 343

14.3 Saturn 343
Saturn's Rings 344
Saturn's Family of Moons 344
Exploration 345

Visualizing Astronomy 14.2 The Ice Rings of Saturn 346

14.4 Uranus and Neptune:Ice Giants 348
Ice Giant Moon Systems 349
Rings 350
Exploration 351

14.5 Dwarf Planets 351
What Defines a Planet? 351
Pluto 351
Ceres 352
Other Dwarf Planets 353

The Big Picture 354

Review and Discussion Questions 355

PART 5 Life 356

15 Life on Other Worlds 356

15.1 The Nature of Life 358
The Physical Basis of Life 358
Information Storage and Duplication 358
Modifying the Information 359

15.2 Life in the Universe 359
The Origin of Life on Earth 359

Visualizing Astronomy 15.1 DNA: The Code of Life 360
Deep Time and the Evolution of Life 364
Life in Our Solar System 365
Life in Other Planetary Systems 368

15.3 Intelligent Life in the Universe 370
Travel Between the Stars 370
Radio Communication 370
How Many Inhabited Worlds? 373

The Big Picture 374

Review and Discussion Questions 374

Afterword 376

Appendix A: Units and Astronomical Data 378
The Metric System and SI Units 378
Temperature Scales 378
Astronomy Units and Constants 378

Appendix B: Observing the Sky 384
Using Star Charts 384
Star Charts 385

Appendix C: Celestial Profiles 387
Mercury 387
Venus 387
Earth 388
Mars 388
Jupiter 389
Saturn 389
Uranus 390
Neptune 390
The Sun 391
The Moon 391

Index 392

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PART ONE

1 The Scale of the Cosmos: Space and Time

CHAPTER OUTLINE

1.1 Astronomy: A Global Human Adventure
1.2 From Solar System to Galaxy to Universe
1.3 The Cosmic Calendar: Concepts of Time

GUIDEPOST

You already know more about astronomy than you may think. You have enjoyed sunsets and moonrises, have admired the stars, and may know a few constellations. You have probably read about Mars rovers and the Hubble Space Telescope. That is more than most Earthlings know about astronomy. Still, you owe it to yourself to understand where you are. You should know what it means to live on a planet that whirls around a star sailing through one galaxy in a universe full of galaxies.

It is easy to learn a few facts, but it is the relationships among facts that are important. This chapter will give you the sense of scale you need in order to appreciate the vastness of the universe and to understand your place within it.

Here, you will consider important questions about astronomy:

- How is astronomy research done today through global collaborations?
- Where are you and Earth in the universe?
- How does the time span of human civilization compare with the age of the universe?
- How does science give us a way to know about nature?

The remaining chapters in this book will fill in the details, give evidence, describe theories, and illustrate the wonderful intricacy and beauty of the universe. That journey begins here.

You are about to go on a voyage to the limits of the known universe, travelling outward, away from your home on Earth, past the Moon and the Sun and the other planets of our solar system, past the stars you see in



NASA

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The spectacular aurora borealis, or the "northern lights," over Canada is sighted from the International Space Station near the highest point of its orbital path. The station's main solar arrays are seen in the left foreground. This photograph was taken by a member of the Expedition 53 crew aboard the station on September 15, 2017.

Space is for everybody. It's not just for a few people in science or math, or for a select group of astronauts. That's our new frontier out there, and it's everybody's business to know about space.

Christa McAuliffe,
teacher and Challenger astronaut

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the night sky, and beyond billions more stars that can be seen only with the aid of telescopes. You will visit the most distant galaxies—great globes and whirlpools of stars—and continue on, carried only by experience and imagination, seeking to understand the structure of the universe. Astronomy is more than the study of planets, stars, and galaxies—it is the study of the whole universe in which you live. Although humanity is confined to a small planet circling an unremarkable star, the study of astronomy can take you beyond these boundaries and help you not only see where you are but also understand *what* you are.

Your imagination is the key to discovery; it will be your scientific space-and-time machine transporting you across the universe and into the past and future. Go back in time to watch the formation of the Sun and Earth, the birth of the first stars, and ultimately the creation of the universe. Then, rush into the future to see what will happen when the Sun dies and Earth withers.

Although you will discover a beginning to the universe, you will not find an edge or an end to space. No matter how far you voyage, you will not run into a wall. In a later chapter you will discover evidence that the universe may be infinite; that is, it may extend in all directions without limit.

Astronomy will introduce you to sizes, distances, and times far beyond your usual experience on Earth. Your task in this chapter is to grasp the meaning of these unfamiliar sizes, distances, and times. The solution lies in a single word: scale. In this chapter, you will compare objects of different sizes in order to comprehend the scale of the universe.

1.1 Astronomy: A Global Human Adventure

Like you, our ancestors viewed the night sky and attempted to make sense out of a bewildering array of white light sources or, simply, stars. Most stars appeared to remain stationary with respect to the other stars. Some were decidedly brighter than others. To a careful observer, a few even appeared faintly blue, orange, or red. A few moved quite significantly with respect to the stable background of stars—and these, initially known as wandering stars, were eventually termed planets. Of course, our ancestors also carefully monitored the comings and goings of the two brightest objects in the sky: the Sun and the Moon.

What was the human mind to make of this? For thousands of years, humans have been assembling their observations of the cosmos into stories, explanations, and models, handing these down from one generation to the next. Astronomy has long been a global effort, from the earliest natural philosophers exchanging concepts among cultures, to seafaring civilizations going on long voyages to make celestial observations, to our modern globally connected scientific community. Human beings have always been united by curiosity about our cosmic origins, and our place in space and time. Today, international coalitions of scientists and engineers come together from around the world to build grand telescopes, and collect observations, and share the results in public databases. Anyone with an Internet connection can access observations of the sky taken by telescopes from across the planet and in space.

Today, we understand that we make our observations of the cosmos from a planet tucked away near the edge of just one of billions of galaxies that populate our expanding universe. We can marvel at the strength and sophistication of the human mind that has enabled us to collectively locate ourselves across vast stretches of space and time.

> People from different backgrounds approach a subject in different ways and ask different questions.
>
> *—Jocelyn Bell Burnell, discoverer of pulsars, neutron stars*

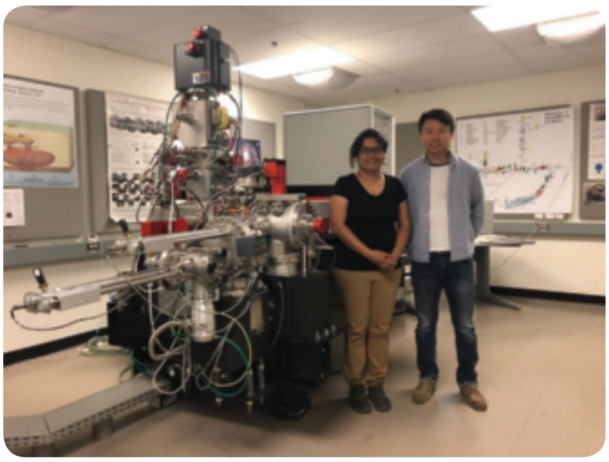
Every culture has brought a unique perspective to the search for answers to challenging questions about our place in space and time. Today scientists attempt to erase political and geographical boundaries and establish global collaborations, so that anyone can access the results of experiments and observations and test their ideas against observed data. An example of such international collaboration is the Large Hadron Collider (see **Visualizing Astronomy 11.1** and Figure 1.1), an enormous technological achievement built and used by over 10 000 scientists and hundreds of universities and laboratories, from more than 100 countries including Canada. One goal of this undertaking is to simulate the early moments of our universe and test the very nature of matter. The Large Hadron Collider has been used to discover fundamental particles in nature that make up all matter in the universe.

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Mike Struik

Figure 1.1 Fabiola Gianotti, an Italian particle physicist and the Director-General of CERN (European Organization for Nuclear Research), in the ATLAS detector of the Large Hadron Collider, for which Canada contributed parts.



Maitrayee Bose/ASU, CC BY-SA

Figure 1.2 Maitrayee Bose (left) and Ziliang Jin (right) as they prepare to measure Itokawa samples.

Another international collaboration, the Event Horizon Telescope (EHT) (see Figure 4.11), has produced the first ever photograph of a black hole in a core of a distant galaxy (see Figure 10.22). The telescope consists of a planet-wide array of telescopes from Europe, Greenland, the United States, Antarctica, and Asia, connected together into a single instrument the size of Earth. Similarly, the Atacama Large Millimeter/submillimeter Array (ALMA) is a radio telescope made of 66 individual radio telescopes in the Atacama Desert in northern Chile (see the opening image of Chapter 9). This important endeavour is a colossal international collaboration involving the United States, the European Union, Canada, South Korea, Japan, and Taiwan.

You might be aware that spacecraft from different countries have been launched to explore various bodies within the solar system and in the process have discovered important details about the origin and composition of planets, moons, asteroids, and comets. The Japanese spacecraft *Hayabusa* was designed to travel to a small near-Earth asteroid (Itokawa), where it hovered close enough to its surface to collect a small sample and then returned to Earth. This journey took seven years to accomplish, and the grains of asteroidal material are now being analyzed for various molecules including water. These precious samples are now a focus of scientific study in laboratories all around the world—such as Arizona State University, where Indian and Chinese cosmochemists Maitrayee Bose and Ziliang Jin are analyzing a sample (Figure 1.2).

In 2014, India's Mars Orbiter Mission (MOM), also called *Mangalyaan*, arrived at the red planet to study its surface and atmospheric features and the effects of the solar wind on the upper atmosphere. Both the National Aeronautics and Space Administration (NASA) and the South African Space Agency provided communications and navigation and tracking support, again demonstrating global cooperation in space exploration (Figure 1.3). The orbiter continues to function as of the time of writing and plans exist for a follow-up mission, MOM-2, to arrive at Mars in the mid-2020s.

In January 2019 the Chinese spacecraft Chang'e 4 became the first moon lander to set down on the side of the Moon invisible from Earth, near the Moon's south pole. The mission's objective is to learn the age and composition of this unexplored area of the Moon called the Aitken basin, where the deep lunar crust may be exposed.

Very often observed results are more surprising than expected, and in order to test the observations, independent



Manjunath Kiran/AFP/Getty Images

Figure 1.3 Staff from the Indian Space Research Organization celebrate after their Mars Orbiter spacecraft successfully entered the Mars orbit on September 24, 2014.

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teams from different parts of the world look at the same phenomena in different ways. In 1998, a team of astronomers from the Supernova Cosmology Project from Berkeley, California, set their instruments to measure the rate of slowing of the expansion of the universe. Their observations showed a surprising result. Contrary to the hypothesis that the expansion rate of the universe was slowing down, the results seemed to indicate that the universe's expansion was accelerating. In a case like this, you would not know if some systematic errors were present in the observing equipment or in the processing of the data unless another team was performing the same observation with different equipment and utilizing another methodology. Fortunately, an international collaboration of astronomers from the United States, Europe, Australia, and Chile were attempting to make the same measurement (see Figure 11.14). Their data confirmed that the surprising outcome was, indeed, correct. Astronomers were suddenly faced with the fact that our universe contains a component or force driving the expansion of the universe faster and faster. This mysterious component is now known as dark energy. You will learn more about dark energy and the beginning and end of the universe in Chapter 11.

As you can see, astronomy is, and has always been, a global effort. If humanity is to unravel the secrets of the universe we must collaborate and build on observations, ideas, and technologies from all around the world. You will come to realize that the study of astronomy also incorporates important concepts from both physical and biological sciences. The story of astronomy is thus a story of collective human knowledge.

1.2 From Solar System to Galaxy to Universe

Your quest to find our place in the visible universe can start anywhere on Earth. Let's launch our journey in the Universe of Particles, a museum exhibit at the Globe of Science and Innovation at CERN (Organisation Européenne pour la Recherche Nucléaire) in Geneva (see **Visualizing Astronomy 1.1, The Scale of the Very Small and Very Large: Powers of 10**). CERN is the home of the Large Hadron Collider, the largest particle accelerator in operation today, which was designed to simulate the beginning of the universe (see also Chapter 11, **Visualizing Astronomy 11.1, The Large Hadron Collider**). Not more than 100 m under the ground from the Globe of Science and Innovation, massive detectors are looking for the first signs of the big bang, microscopic black holes, and dark matter. The results might shed light on many topics in this book, and perhaps even change a few chapters. You indeed live in exciting times, when new technology can bring us closer to our origins.

scientific notation The system of recording very large or very small numbers by using powers of 10.

field of view The area visible in an image, usually given as the diameter of the region.

Now let's use our imagination to fly out from the Globe of Science and Innovation. Along the way, study the journey described in **Visualizing Astronomy 1.1, The Scale of the Very Small and Very Large: Powers of 10**. (The following figure numbers refer to these pages.)

Your journey to the smallest realm of nature starts with the human hand on the museum exhibit (Figure 1a). To reach the scale of skin cells in your hand (Figure 1b), you have to zoom in with a microscope 100 000 times to a size that is 100-thousandth of a metre. The metre quickly becomes too large as a unit. Instead we use either prefixes (e.g., "milli," which means "one-thousandth") or **scientific notation**—the powers of 10. The information about the cell and the organism to which the cell belongs is encoded in the DNA molecule. The DNA strand shown here is a billionth of a metre thick (Figure 1c). Diving through the molecule, you encounter the main building block of matter: the atom. The size of the electron cloud surrounding the tiny nucleus of an atom is 10-billionth of a metre (Figure 1d). The nucleus of the atom is 10 000 times smaller than the atom itself. Elementary particles are roughly in the order of 10 times smaller than the nucleus. How far can we go? Large Hadron Collider achieved collisions in which a Higgs boson has been produced, on the scale of 10^{-15} m (Figure 1e). The smallest length that theoretically makes sense is the Planck length—100 billion billion times smaller than the scale of the smallest elementary particles (Figure 1f). An understanding of these building blocks of space and matter allows you to unravel the secrets of the birth and evolution of the universe.

In the following chapters you will embark on a journey from Earth to the farthest visible extent of the universe. For those distances you can use larger measures than the metre as you move outward from Earth.

You will now follow the sequence in **Visualizing Astronomy 1.1, The Scale of the Very Small and Very Large: Powers of 10**, starting again from the Globe of Science and Innovation (Figure 2a), and moving farther and farther away. Each view is made from a distance that is some power of 10 times farther away, until the distance becomes so large that we jump with higher increments. Every time you move 10 times away, your **field of view** encompasses an area 10 × 10 larger than the previous square.

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Distances are first expressed in metres until they become so large that a metre becomes too small as a unit. At a distance of 10 000 m, or 10 km, the view includes about the same area as CERN's Large Hadron Collider (Figure 2b).

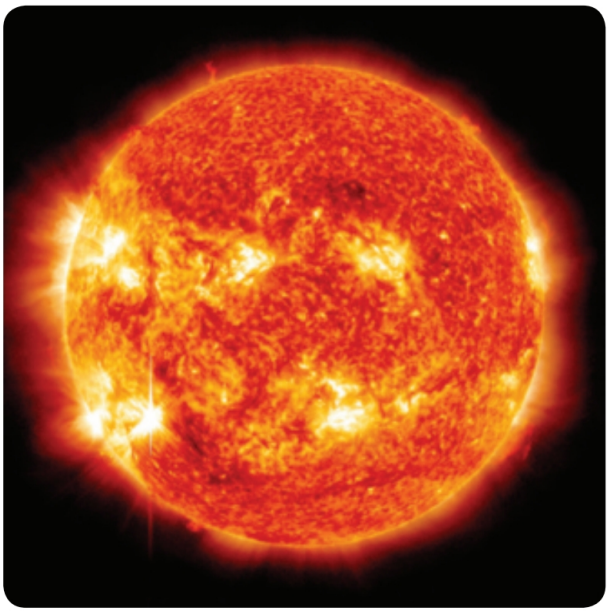
In the next step of the journey, you can see the entire planet Earth, which is about 13 000 kilometres in diameter. The image of Earth (Figure 2c) shows most of the daylight side of the planet, and the blurriness at the extreme right is the sunset line. The rotation of Earth on its axis each 24 hours carries you eastward, and as you cross the sunset line into darkness, we say that the Sun has set. At the scale of this image, the atmosphere on which our life depends is thinner than a strand of thread.

Next you enlarge field of view by a factor of 100 and see a region 1 000 000 km wide (Figure 2d). Earth is the small blue dot in the centre, and the Moon, with a diameter only about one-fourth that of Earth, is an even smaller dot along its orbit. If you've had a high-mileage car, it may have travelled the equivalent of a trip to the Moon, which has an average distance from Earth of 380 000 km. These numbers are so large that it is inconvenient to write them out. Astronomy is the science of big numbers, and you will use numbers much larger than these to describe the universe.

Here, you jump to another measuring unit. You enlarge a picture not 10 times or 100 times, but 150 times in order to fit a specific distance into the picture: the average distance from Earth to the Sun. This distance is called the **astronomical unit (AU)**, which is 1.5×10^8 km, or 1.5×10^{11} m. Introducing new units is another way astronomers deal with large numbers. Using that unit, you can say, for example, that the average distance from Venus to the Sun is about 0.7 AU. At this scale you find the Sun and a few of the inner planets of our solar system (Figure 2e). The **solar system** consists of the Sun, its family of planets, and some smaller bodies, such as moons, asteroids, and comets.

Like Earth, Venus and Mercury are **planets**—small, nonluminous bodies that shine by reflecting sunlight. Venus is about the size of Earth, and Mercury is a bit larger than Earth's moon. In this figure they are both too small to be seen as anything but tiny dots. The Sun is a **star**, a self-luminous ball of hot gas that generates its own energy (Figure 1.4). The Sun is about 110 times larger in diameter than Earth, but it, too, is nothing more than a dot in this view. Earth orbits the Sun once a year.

Now, jump 100 times farther away than the previous view, and you will see the entire solar system, all the major planets and their slightly elliptical orbits (Figure 2f). You see only the brighter, more widely separated objects



NASA

Figure 1.4 Our Star: The Sun

as you back away. The Sun, Mercury, Venus, and Earth are so close together that you cannot separate them at this scale.

Mars, the next outward planet, is only 1.5 AU from the Sun. In contrast, Jupiter, Saturn, Uranus, and Neptune are so far from the Sun that they are easy to find in this figure. Light from the Sun reaches Earth in only eight minutes, but it takes over four hours to reach Neptune. Pluto, which orbits mostly outside Neptune's orbit, is no longer considered a major planet.

The Sun is a fairly typical star, a bit larger than average, and it is located in a fairly normal neighbourhood in the galaxy. The stars are separated by average distances about 30 times larger than this view, which has a diameter of 11 000 AU. It is difficult to grasp the isolation of the stars. If the Sun were represented by a golf ball in Vancouver, the nearest star would be another golf ball in Calgary.

At this point, our view has expanded to a diameter of about 2 million AU. The Sun is at the centre, and you see a few of the nearest stars. These stars are so distant that it is not reasonable to give

astronomical unit (AU) Average distance from Earth to the Sun; 1.5×10^8 kilometres.

solar system The Sun and its planets, asteroids, comets, and so on.

planet A nonluminous body in orbit around a star, large enough to be spherical and to have cleared its orbital zone of other objects.

star A globe of gas held together by its own gravity and supported by the internal pressure of its hot gases, which generate energy by nuclear fusion.

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VISUALIZING ASTRONOMY 1.1

The Scale of the Very Small and Very Large: Powers of 10



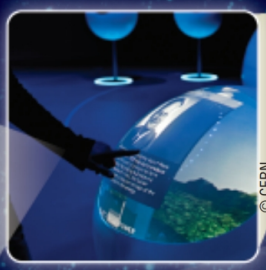
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2

1

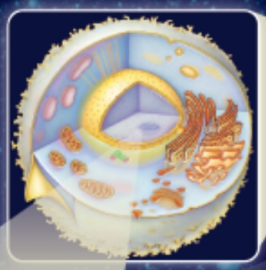
This view, about 20 m in diameter, is inside the Universe of Particles, a museum exhibit at the Globe of Science and Innovation at CERN (Organisation Européenne pour la Recherche Nucléaire) in Geneva (Figure 2).



© CERN

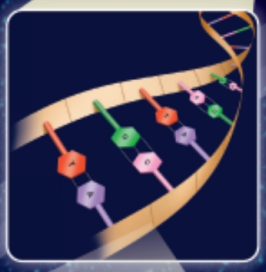
1a

1 m from museum exhibit



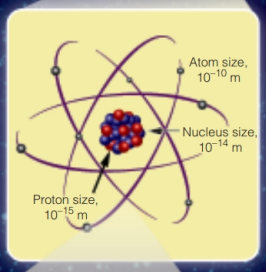
1b

Body cell, 10^{-5} m



1c

Thickness of DNA, 10^{-9} m



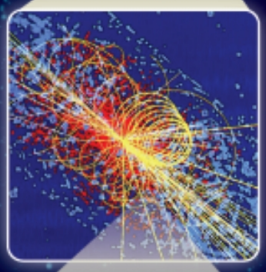
Mr.Jafari / Shutterstock.com

1d

Atom size, 10^{-10} m

Each area of astronomy and related multidisciplinary sciences (such as astrobiology and astrochemistry) explores a different realm of nature, from the smallest structures in the universe to the largest. The study of the production of energy in stars involves the study of an atomic nucleus, while cosmology studies the structure and evolution of the universe on the largest scale. To understand the vast range of sizes and distances on our journey to understanding nature, we have to adopt symbols for very small and very large numbers. It is not convenient to express the size of an atom as 0.0000000001 m or the far distance observed in the universe as 100 000 000 000 000 000 000 000 000 m. Instead, we use either **prefixes** (e.g., "kilo," which means "one thousand") or **scientific notation** (i.e., powers of 10). Here are some examples:

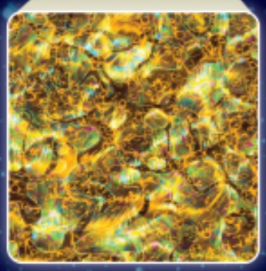
1 billionth of a metre (**nano**metre, nm) = 0.000000001 m = 10^{-9} m
1 millionth of a metre (**micro**metre, μm) = 0.000001 m = 10^{-6} m
1 thousandth of a metre (**milli**metre, mm) = 0.001 m = 10^{-3} m
1 hundredth of a metre (**centi**metre, cm) = 0.01 m = 10^{-2} m
1 thousand metres (**kilo**metre, km) = 1000 m = 10^{3} m
1 million (**mega**) metres = 1 000 000 = 10^{6} m
1 billion (**giga**) metres = 1 000 000 000 = 10^{9} m



© Lucas Taylor/CMS. CERN

1e

Computer simulation of particle traces from a Large Hadron Collider collision in which a Higgs boson is produced, 10^{-15} m



MEHAU KULYK / SCIENCE PHOTO LIBRARY

1f

Planck length, 10^{-35} m

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2a

100 m from CERN's Globe of Science and Innovation



Imagery ©2014 TerraMetrics. Map data ©2014 Google

2b

CERN site aerial view, 10^4 m = 10 km



NASA

2c

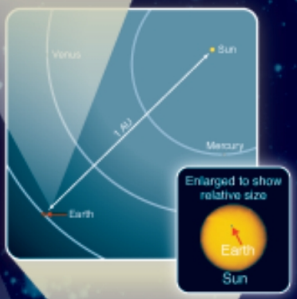
Earth, 10^7 m = 10^4 km



NASA

2d

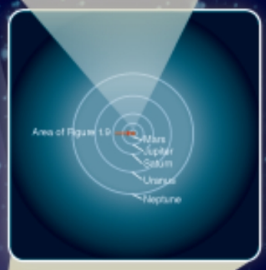
Earth with the Moon, 10^6 km



NASA

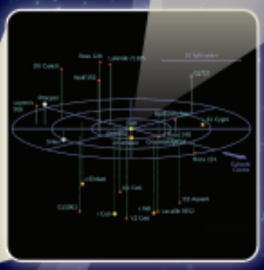
2e

Solar system inside Earth's orbit, 1.5×10^{11} m. This distance is called the **astronomical unit**.



2f

Orbits of solar system, 150 AU, about 10^{13} m

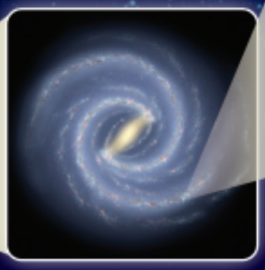


ESO/R.-D.Scholz et al. (AIP)

2g

Some closest stars to our Sun within 30 ly, 3×10^{17} m

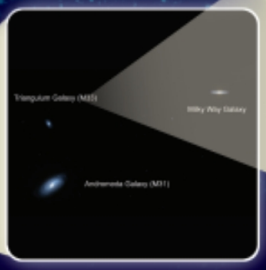
NASA/JPL-Caltech/ESO/R. Hurt



2h

Milky Way, our galaxy, 10^5 ly, 10^{21} m

NASA. Screen capture of http://svs.gsfc.nasa.gov/30955. Frank Summers (STScI), Gurtina Besla (Columbia University), and Roeland van der Marel (STScI)

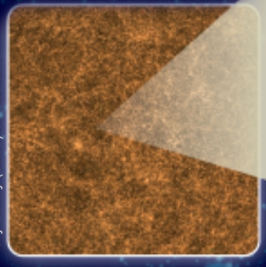


2i

Local Group of galaxies, 4×10^6 ly, 4×10^{22} m

2j

The view with a diameter of 1.7 billion light-years. This image is a fragment of an all-sky survey created by SDSS (Sloan Digital Sky Survey), capturing a quarter of a billion stars and a quarter of a billion galaxies. It shows clusters of galaxies connected in a vast network.



Michael Blanton and the Sloan Digital Sky Survey (SDSS) Collaboration

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their distances in AU. Astronomers have defined a new larger unit of distance, the light-year. One **light-year (ly)** is the distance that light travels in one year, roughly 10^{13} km, or 63 000 AU. In the diagram of the nearby stars in relation to the Sun (Figure 2g), the diameter of our view is 30 ly. The nearest star to the Sun, Proxima Centauri, is 4.2 ly from Earth. In other words, light from Proxima Centauri takes 4.2 years to reach Earth.

Although these stars are roughly the same size as the Sun, they are so far away that you cannot see them as anything but points of light. Even with the largest telescopes on Earth, you still see only points of light when you look at stars, and any planets that might circle those stars are much too small and faint to be visible. Of course, no one has ever journeyed thousands of light-years from Earth to look back and photograph the Sun's neighbourhood.

The space between the stars is filled with thin gas. Although those clouds of gas are thinner than the best vacuum produced in laboratories on Earth, it is those clouds that give birth to new stars. The Sun formed from such a cloud about 5 billion years ago.

Expanding your view by a factor of 3000, you see our galaxy (Figure 2h). A **galaxy** is a great cloud of stars, gas, and dust bound together by the combined gravity of all the matter. In the night sky, you see our galaxy from the inside as a great, cloudy band of stars ringing the sky as the **Milky Way**, and our galaxy is called the **Milky Way Galaxy**. Of course, no one has photographed our galaxy, but astronomers have evidence that the galaxy image in Figure 2h is similar to our own. Our Sun would be invisible in such a picture, but if you could see it, you would find it about two-thirds of the way from the centre to the edge. Our galaxy contains over 100 billion stars, and, like many others, has graceful **spiral arms** winding outward through the disk. You will discover in a later chapter that stars are born in great clouds of gas and dust as they pass through the spiral arms.

light-year (ly) Unit of distance equal to the distance light travels in one year.

galaxy A large system of stars, star clusters, gas, dust, and nebulae orbiting a common centre of mass.

Milky Way The hazy band of light that circles our sky, produced by the glow of our galaxy.

Milky Way Galaxy The spiral galaxy containing our Sun, visible in the night sky as the Milky Way.

spiral arms Long spiral pattern of bright stars, star clusters, gas, and dust. Spiral arms extend from the centre to the edge of the disk of spiral galaxies.

supercluster A cluster of galaxy clusters.

The visible disk of our galaxy is roughly 100 000 ly in diameter, but the most recent data from large international surveys of stars in the Milky Way Galaxy indicate the size of the disk to be much larger. Only a century ago, astronomers thought it was the entire universe—an island universe of stars in an otherwise empty vastness. Now we know that the Milky Way Galaxy is not unique; it is a typical galaxy in many respects, although larger than most. In fact, ours is only one of many billions of galaxies scattered throughout the universe.

Continuing our journey from the very small to the very large, we move away 40 times farther, and our galaxy appears as a tiny luminous speck surrounded by other specks in a region 4 million ly in diameter. Notice that our galaxy is part of a cluster of a few dozen galaxies called the Local Group (Figure 2i). Galaxies are commonly grouped together in clusters, and some of these galaxies have beautiful spiral patterns like our own galaxy but others do not. In a later chapter you will investigate what produces these differences among the galaxies.

The image of a fragment of an all-sky survey created by SDSS (Sloan Digital Sky Survey) captures a quarter of a billion galaxies and represents a diameter of 1.7 billion light-years (Figure 2j). It shows clusters of galaxies connected in a vast network. Clusters are grouped into **superclusters**—clusters of clusters—and the superclusters are linked to form long filaments and walls outlining voids that seem nearly empty of galaxies. These filaments and walls appear to be the largest structures in the universe.

If we expanded our view frame one more time, we would probably see a uniform fog of filaments and voids. As we puzzle over the origin of these structures we are at the frontier of human knowledge. The sequence of figures ends here because it has reached the limits of possible observation of the universe. It is not possible to see any distance larger than 13.8 billion light-years. If the universe is 13.8 billion years old, the light from distances farther away than this would not have had the time to reach us. You will learn more about cosmology in Chapter 11.

A problem in studying astronomy is keeping a proper sense of scale. Remember that each of the billions of galaxies contains billions of stars. Many of those stars probably have families of planets like our solar system, and on some of those billions of planets liquid-water oceans and protective atmospheres may have sheltered the spark of life. It is possible that some other planets are inhabited by intelligent creatures who share our curiosity, wonder at the scale of the cosmos, and are looking back at us when we gaze into the heavens.

How could anyone possibly know these secrets of nature? Science gives us a way to know how nature works (see **How Do We Know? 1.1** and **How Do We Know? 1.2**). As you explore the universe in the chapters that follow, notice not only *what* is known but also *how* it is known.

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HOW DO WE KNOW? 1.1



The Scientific Method I

How do scientists learn about nature? You have probably heard of the *scientific method* as the process by which scientists form hypotheses and test them against evidence gathered by experiment and observation. Scientists use the scientific method all the time, and it is critically important, but they rarely think of it. It is such an ingrained way of thinking and understanding nature that it is almost invisible to the people who use it most.

A hypothesis is a suggestion about how nature works, and the evidence is reality. If a hypothesis is compared to the evidence and confirmed, it must be tested further; if it is contradicted, it must be discarded or revised. In that way, ideas get tested and refined to better describe how nature works.

For example, Gregor Mendel (1822–1884) was an Austrian abbot who liked gardening. He formed a hypothesis that offspring usually inherit traits from their parents, not as a smooth blend as most scientists of the time believed, but as discrete units according to strict mathematical rules. Mendel cultivated and tested more than 28 000 pea plants, noting which produced smooth peas and which produced wrinkled peas and how that trait and others were inherited by successive generations. His studies confirmed his hypothesis and allowed the development of a series of laws of inheritance. Although the importance of his work was not recognized in his lifetime, Mendel is now called the father of modern genetics.

The scientific method is not a simple, mechanical way of grinding facts into understanding. It is actually a combination of many ways of analyzing information, finding relationships, and creating new ideas. A scientist needs insight and ingenuity to form and test a good hypothesis. Scientists use the scientific method almost automatically, forming, testing, revising, and discarding hypotheses sometimes minute-by-minute as they discuss new ideas. The so-called scientific method is a way of thinking and a way of knowing about nature. The **How Do We Know?** essays in this book will introduce you to some of the methods scientists use.

HOW DO WE KNOW? 1.2



The Scientific Method II

How do scientists describe the laws of nature? Mathematics is a language that uses symbols to represent quantities that describe physical properties (mass, charge, energy, speed, etc.). The language of science precisely expresses complicated relationships among physical properties by using mathematical equations.

A simple example involves the well-known scientific equation $F = ma$. In this equation, F is the force applied to an object, m is the mass of the object (amount of matter or stuff it contains), and a is its acceleration. We can translate the mathematical shorthand into a plain language sentence about the relationship among the three quantities force, mass, and acceleration: The more force you apply to an object, the more it accelerates. If you apply twice as much force the acceleration exactly doubles (assuming the mass remains the same). In mathematical terms we say that the force applied is directly proportional to the acceleration of the object of constant mass m. And the reverse applies too. The acceleration

Continued

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HOW DO WE KNOW? 1.2 *(Continued)*



of the object is directly proportional to the total force you can apply. You have experienced this relationship for yourself if you have ever tried to push an object like a cart. The harder you push (more force), the faster the cart goes (more acceleration). The equation $F = ma$ captures this idea in a precise and concise way. Not only does it express the relationship, but it also allows us to precisely calculate "how much harder" and "how much faster."

Sometimes the relationship between physical quantities is an inverse proportionality. For example, consider the equation $u = d/t$. Here, u is the speed of an object, d is the distance travelled, and t is the time taken to travel the distance d. In this equation, u and t are inversely proportional to each other—so the higher the speed of travel the shorter the time taken to travel a fixed distance d, and vice versa. And like the previous case, the relationship is precise: for example, if you double the speed, you cut your travel time exactly by half.

Although plain language sentences can be used to understand the laws of nature and the relationships between different quantities, as described above, the language of mathematics captures these relationships in the most accurate and concise way. If you understand the relationships encoded in a mathematical equation, you can grasp the science of astronomy without just memorizing mathematical formulas as a "recipe." In the main text of this book, most mathematical equations are described in plain language that describes the relationships between physical quantities. If you want to see the same relationships presented in the form of equations, check the Math Reference Cards at the back of the book. Try to understand the relationships expressed in the math equations after you have read the corresponding description in the text. Soon you will become fluent in this beautiful and elegant language of the universe.

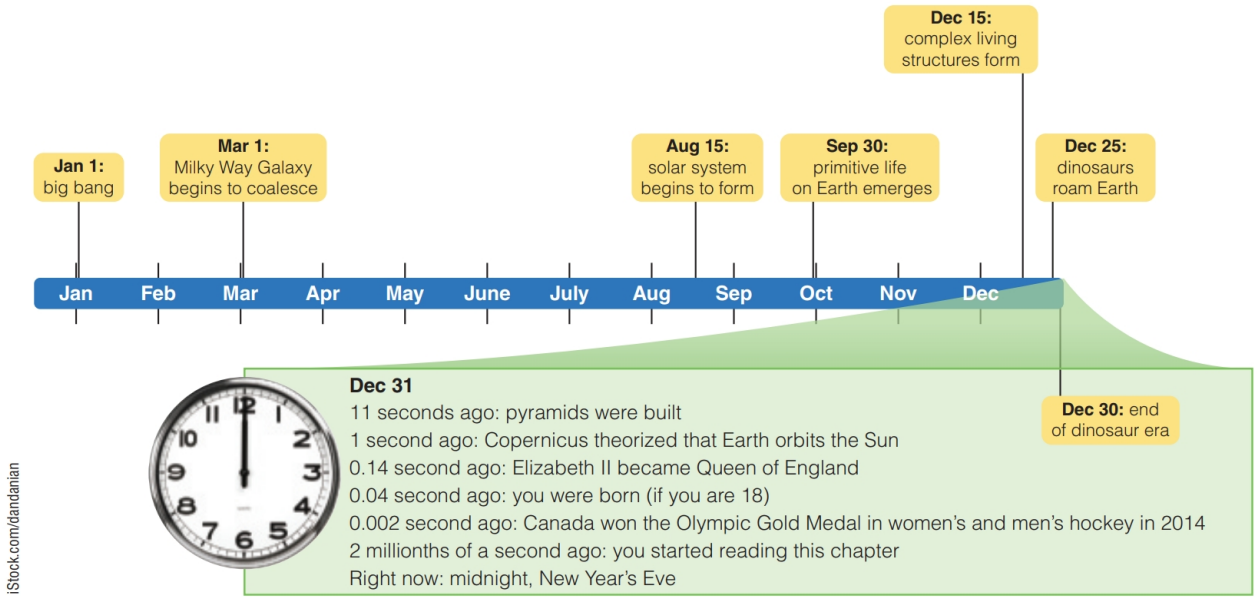
1.3 The Cosmic Calendar: Concepts of Time

In the first part of this chapter you were taken on a journey through the universe from a spatial perspective to give you a sense of the immensity of the universe and how small our little corner of it really is. Equally important is that you gain an appreciation for the concept of time and how the average human lifetime, for instance, compares to the age of the universe. Our current understanding of the formation of the universe and its age leads us to believe that it has been about 13.8 billion years since the big bang, the instant the universe commenced and, perhaps, the beginning of time itself.

Let's imagine that the time our universe has existed is spread over a one-year calendar where each month is a little in excess of 1 billion years—we have, then, a cosmic calendar (a concept devised by Carl Sagan, a well-known astronomer in the latter part of the 1900s). As shown in the timeline in Figure 1.5, the big bang occurred precisely at midnight on January 1; the Milky Way Galaxy starts to coalesce in late February or early March, which makes it one of the oldest galaxies (although there remains debate about the age of the galaxy, recent estimates place its age possibly as old as 13 billion years). Our solar system starts being built around mid-August, and by the end of September primitive life exists on Earth. However, it is not until mid-December on this cosmic calendar that complex living structures such as invertebrate life formed—and not until December 25 when dinosaurs roamed Earth. The end of the dinosaur era, which took place 65 million years ago, occurred yesterday, December 30, on the cosmic calendar.

The next day, December 31, is when all of recorded history occurred and even then not until much later in the day—within the last 30 seconds, in fact. The Egyptian pyramids were built about 11 seconds ago; Copernicus and others convinced humanity that

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iStock.com/dandanian

Figure 1.5 The Cosmic Year: A Timeline

Earth orbits the Sun about one second ago; Elizabeth II became Queen of England about 0.14 seconds ago; you were born about 0.04 seconds ago (assuming your age is 18); Canada won the 2014 Olympic Gold Medal in women's and men's hockey about 0.002 seconds ago; you started reading this chapter about 2 millionths of a second ago; and it is now exactly midnight on December 31—Happy New Year!

The **Big Picture**

Astronomy is important because it helps us understand what we are. We human beings live on the surface of planet Earth as it orbits the star we call the Sun. What are we? How did we and our planet and our star come to be here, and what does the future hold for us? Astronomy helps us answer those questions.

Our journey of discovery of the cosmos has led us to the amazing realization that we are intimately linked to the stars. Gravity and atoms work together to make stars, light the universe, generate energy, and create the chemical elements in our bodies. The atoms in our bodies were made deep inside stars, perhaps in a faraway galaxy. Stars died so that we could live! On the atomic level, we all have the same origins. Our similarities are far greater than our differences.

It's easy to be absorbed in our everyday lives and problems. But astronomy helps us appreciate humanity's place in the cosmos. We are part of a grand cycle of birth and death of stars. Although perhaps insignificant in space and time, life on Earth is a precious and fragile example of what the universe can produce over billions of years. Astronomy enriches our lives and gives us perspective on what it means to be here on Earth. Studying the stars and other planets enables us to be better caretakers of our own home: planet Earth.

The story of astronomy is a global story. Ancient civilizations all over the world observed the skies, and astronomy played a critical role in the development of art and culture, festivals and traditions. Our modern understanding of the universe is based on the discoveries of astronomers from around the world. Today, many nations, including Canada, work together on the International Space Station. Astronomy unites us in our journeys of self-knowledge and quests for the stars.

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Review and Discussion Questions

Review Questions

1. What is the largest dimension of which you have personal knowledge? Have you run a mile? Hiked 10 km? Run a marathon?
2. What is the difference between our solar system and our galaxy? Between our galaxy and the universe?
3. Why are light-years more convenient than kilometres or astronomical units for measuring certain distances?
4. Why is it difficult to detect planets orbiting other stars?
5. What does the size of the star image in a photograph tell you?
6. What is the difference between the Milky Way and the Milky Way Galaxy?
7. What are the largest known structures in the universe?
8. How does astronomy help answer the question, "What are we?"
9. **How Do We Know?** How does the scientific method give scientists a way to know about nature?

Discussion Questions

1. Do you think you have a duty to know the astronomy described in this chapter? Can you think of ways this knowledge helps you enjoy a richer life and be a better citizen?
2. How is a statement in a political speech different from a statement in a scientific discussion? Find examples in newspapers, magazines, and this book.

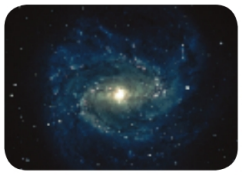
Learning to Look

1. In the image shown here the division between daylight and darkness is at the right on the globe of Earth. How do you know this is the sunset line and not the sunrise line?



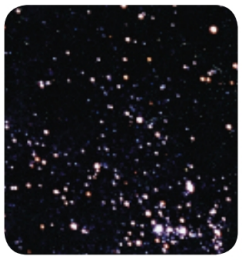
NASA

2. Of the objects listed here, which would be contained inside the object shown in the photograph? Which would contain the object in the photo?
   - stars
   - planets
   - galaxy clusters
   - spiral arms



Bill Schoening/ NOAO/AURA/NSF

3. In the photograph shown here, which stars are brightest, and which are faintest? How can you tell? Why can't you tell which stars in this photograph are biggest or which have planets?



NOAO/AURA/NSF

STUDY TOOLS

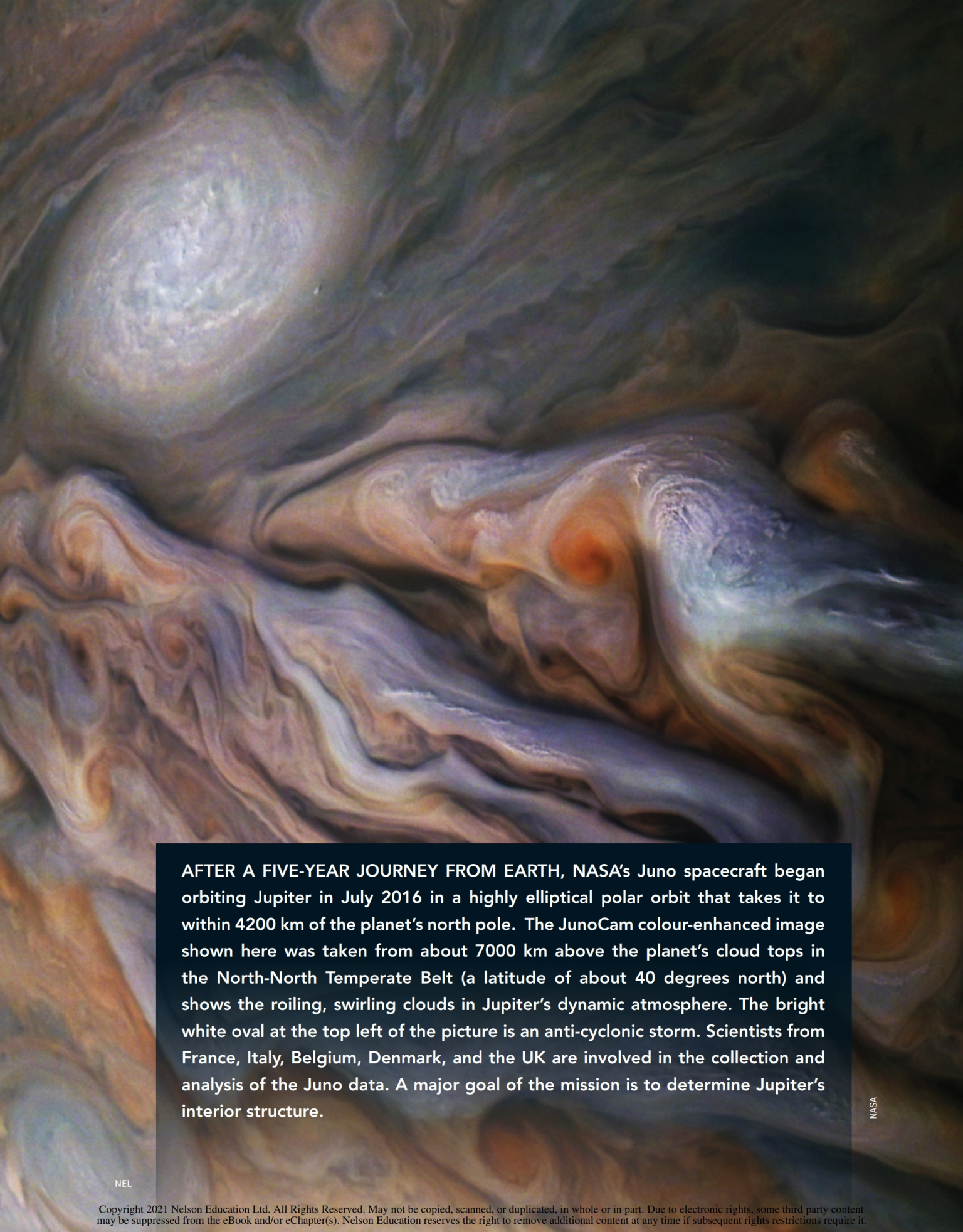
IN THE BOOK

- Tear Out the Review Card on *The Scale of the Cosmos: Space and Time.*

ONLINE

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AFTER A FIVE-YEAR JOURNEY FROM EARTH, NASA's Juno spacecraft began orbiting Jupiter in July 2016 in a highly elliptical polar orbit that takes it to within 4200 km of the planet's north pole. The JunoCam colour-enhanced image shown here was taken from about 7000 km above the planet's cloud tops in the North-North Temperate Belt (a latitude of about 40 degrees north) and shows the roiling, swirling clouds in Jupiter's dynamic atmosphere. The bright white oval at the top left of the picture is an anti-cyclonic storm. Scientists from France, Italy, Belgium, Denmark, and the UK are involved in the collection and analysis of the Juno data. A major goal of the mission is to determine Jupiter's interior structure.

NASA

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PART ONE

2 User's Guide to the Sky: Patterns and Cycles



Jimmy Hu / Shutterstock.com

CHAPTER OUTLINE

2.1 The Stars
2.2 The Sky and Its Motions
2.3 The Cycle of the Sun
2.4 The Cycles of the Moon
2.5 Eclipses
2.6 Stellar Coordinates
2.7 Timekeeping
2.8 Night Sky Tours

GUIDEPOST

The night sky is the rest of the universe seen from our planet. The previous chapter took you on a cosmic zoom out into the sky through deep space and deep time, setting the stage for the drama to come. In this chapter, your exploration will continue with a view of the sky from Earth with unaided eyes. You will discover that the turning of Earth on its axis and its orbital motion around the Sun produce corresponding motions in the sky. You will see how the Sun, Moon, and planets move against the background of stars. Some of those motions have direct influences on your life and produce wonderful sights. As you explore, you will find answers to four important questions:

- How can you refer to stars by name, by constellation, and by brightness?
- How does the sky appear to move as Earth rotates and revolves?
- What causes the seasons?
- How does the motion of the Moon produce phases and eclipses?

As you study the sky and its motions, you can begin to think of Earth as a planet moving through space. The next chapter tells the story of how humans first understood that Earth is a planet.

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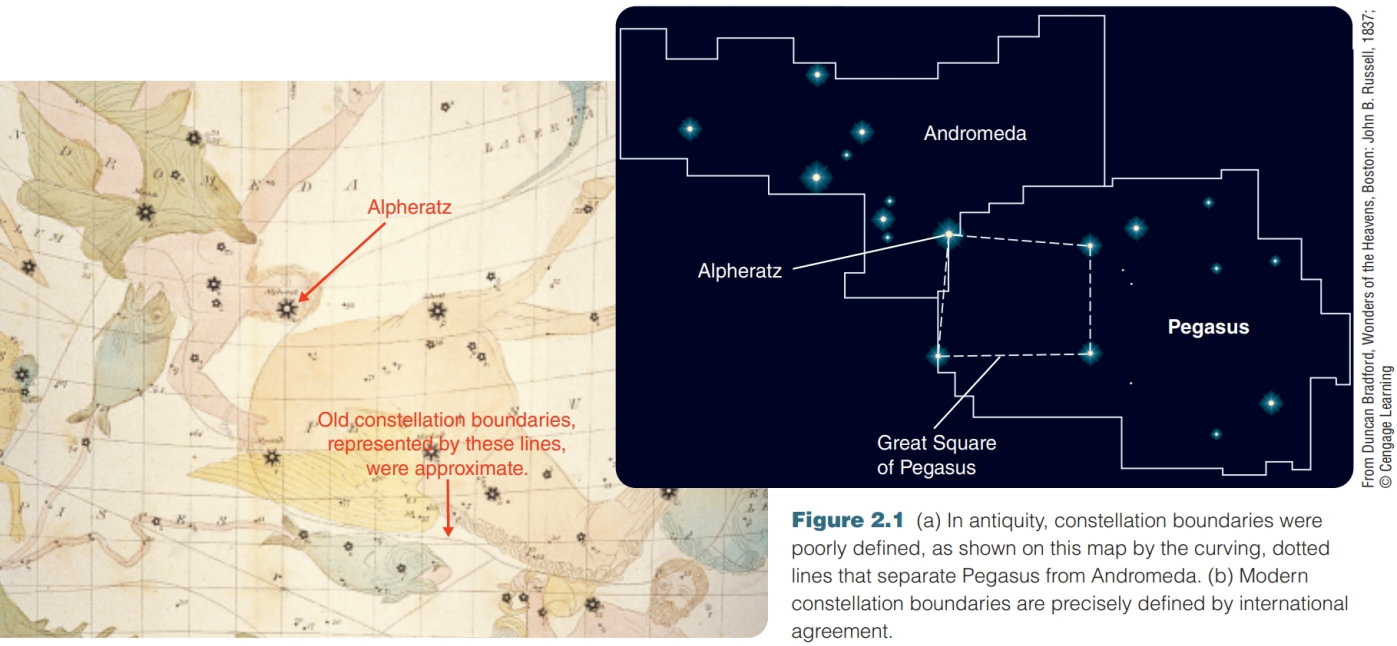


Total solar eclipses are magnificent and memorable events. In August 2017 the path of totality swept across the United States from Oregon to South Carolina. This time-lapse image was taken from an open field near Madras, Oregon.

Do not look at stars as bright spots only. Try to take in the vastness of the universe.

Maria Mitchell, astronomer

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From Duncan Bradford, Wonders of the Heavens, Boston: John B. Russell, 1837; © Cengage Learning

Figure 2.1 (a) In antiquity, constellation boundaries were poorly defined, as shown on this map by the curving, dotted lines that separate Pegasus from Andromeda. (b) Modern constellation boundaries are precisely defined by international agreement.

2.1 The Stars

At least 85 percent of Canadians live in large or medium-sized cities. Consequently, many of us have no appreciation of what lies above us in the night sky owing mainly to light pollution and/or local sight lines. However, if you have ever had the opportunity to view the night sky from a darkened rural region or a family cottage setting you have experienced a wondrous vista.

To the novice viewer it can be a bewildering experience as they scan what appears to be a random scattering of some very bright stars, even more that are of medium brilliance, and hundreds of faint dots filling the night sky sighted in every direction. In fact, the average viewer can identify around 3000 individual stars on a clear, moonless evening.

Constellations

As you study the night sky further you may recognize a few familiar groupings such as the row of three stars in Orion's belt (visible in the southern winter sky) or the Big Dipper, readily observable in the northern sky at any time of the year from any Canadian location. Ancient cultures from all over the world saw pretty much the same confusing night sky as you do today. This fact may surprise you, because you probably know that all stars are moving relative to Earth, some at quite high speeds, but the stars are so far away that it will take thousands of years before we will see an appreciable change in stellar patterns. Ancient cultures from all over the world began organizing the stars by naming groups of stars, called **constellations**, after mythological creatures and gods. You should not be surprised that these star patterns do not look like the figures after which they are named any more than Victoria, British Columbia, looks like Queen Victoria.

constellation One of the stellar patterns identified by name, usually of mythological gods, people, animals, or objects; also the region of the sky containing that star pattern.

Many of today's constellations took root in the imaginations of the civilizations of Mesopotamia, Babylon, Egypt, and Greece as many as 5000 years ago. Of those ancient constellations, 48 are still in use. In those former times, a constellation was simply a loose grouping of bright stars, and many of the fainter stars were not included in any constellation.

Many regions of the southern sky not visible to ancient astronomers living at northern latitudes were not identified with any constellations. Constellation boundaries, when they were defined at all, were only approximate, so a star like Alpheratz could be thought of both as part of Pegasus and as part of Andromeda (Figure 2.1).

In recent centuries astronomers have added 40 modern constellations to fill gaps, and in 1928 the International Astronomical Union (IAU) established a total of 88 official constellations with clearly defined permanent boundaries that together cover the entire sky.

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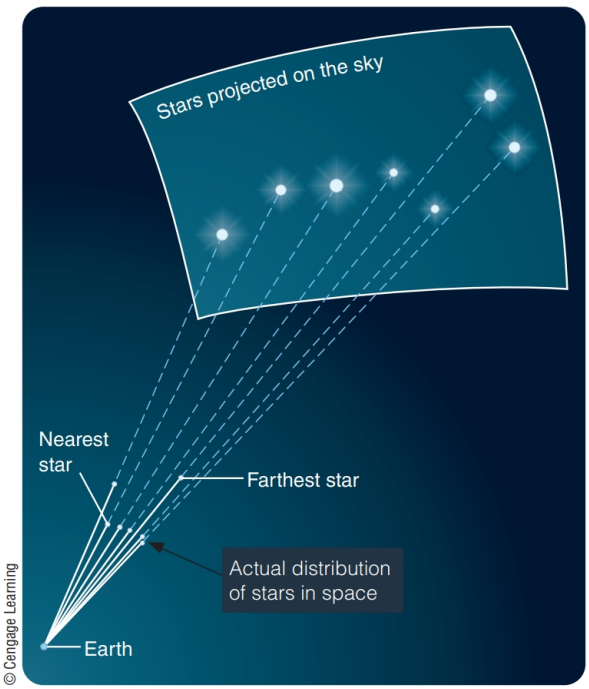
A constellation now represents not a group of stars but a section of the sky—a viewing direction—and any star within the region belongs only to that one constellation.

In addition to the 88 official constellations, the sky contains a number of less formally defined groupings called **asterisms**. Many people think of the Big Dipper as a constellation when, in fact, it is an asterism within the constellation Ursa Major (the Great Bear). The constellation Sagittarius (the Archer) contains an asterism called the Teapot, actually the archer's bow, with even a little nebulosity around the teapot spout representing steam.

Constellations and asterisms are named as if they were real groupings, but most are made up of stars that are not physically associated with one another. Some stars within a given constellation may be many times farther away than others and moving through space with very different speeds and in different directions. The only thing they have in common is that they lie in approximately the same direction as viewed from Earth (see Figure 2.2).

The Names of Stars

In addition to naming groups of stars, early astronomers named many of the brighter stars with names we use today.



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Figure 2.2 The stars you see in the Big Dipper are not at the same distance from Earth. You see the stars in a group in the sky because they lie in the same general direction as seen from Earth, not because they are all actually near each other. The sizes of the star dots in the figure represent the apparent brightness of the stars.

Most individual star names derive from ancient Arabic, much altered over centuries. For example, the name of Betelgeuse, the bright red star in Orion, comes from the Arabic phrase *yad aljawza,* meaning "armpit of Jawza" (Orion). Aldebaran, the bright red eye of Taurus the bull, comes from the Arabic *al-dabar an,* meaning "the follower" (of Pleiades—a well-known open cluster of stars in Taurus).

Another way we identify stars is to assign Greek letters to the bright stars in a constellation in approximate order of brightness. The brightest star is usually designated alpha (α), the second brightest beta (β), the first and second letters of the Greek alphabet, and so on. For many constellations, the letters follow the order of brightness, but some constellations, such as Orion, are exceptions (Figure 2.3). A Greek-letter star name also includes the possessive Latin form of the constellation name; for example, the brightest star in the constellation Canis Major is alpha Canis Majoris. This name identifies the star and the constellation and gives a clue to the relative brightness of the star. Compare this with the ancient individual name for that star, Sirius, which tells you nothing about its location or brightness.

The Brightness of Stars

Based on the foregoing it is evident that stellar brightness is an important quality. Astronomers measure the apparent brightness of stars using the **magnitude scale**. Early astronomers divided the stars into six brightness groups. The brightest were called first-magnitude stars, the next brightest were called second-magnitude, and so on downward to sixth-magnitude stars, the faintest visible to the human eye. Thus, the *larger* the magnitude number, the *fainter* the star.

The Greek astronomer Hipparchus (190–120 BCE) is believed to be the first to catalogue stars by their apparent brightness, which observers of the time perceived as related to size, hence the term *magnitude*. Later, around 140 CE, Claudius Ptolemy definitely used the magnitude system in his own catalogue. By the mid-19th century astronomers realized that magnitudes had nothing to do with the angular sizes of stars because all stars were so far away as to appear as point sources of light. Rather, the brightness of a star was related to the intensity of the light produced by the star along with its distance from Earth. Furthermore, using photometric measurements, it was determined that first-magnitude stars are about 100 times brighter

asterism A named grouping of stars that is not one of the recognized constellations.

magnitude scale The astronomical brightness scale; the larger the number, the fainter the star.

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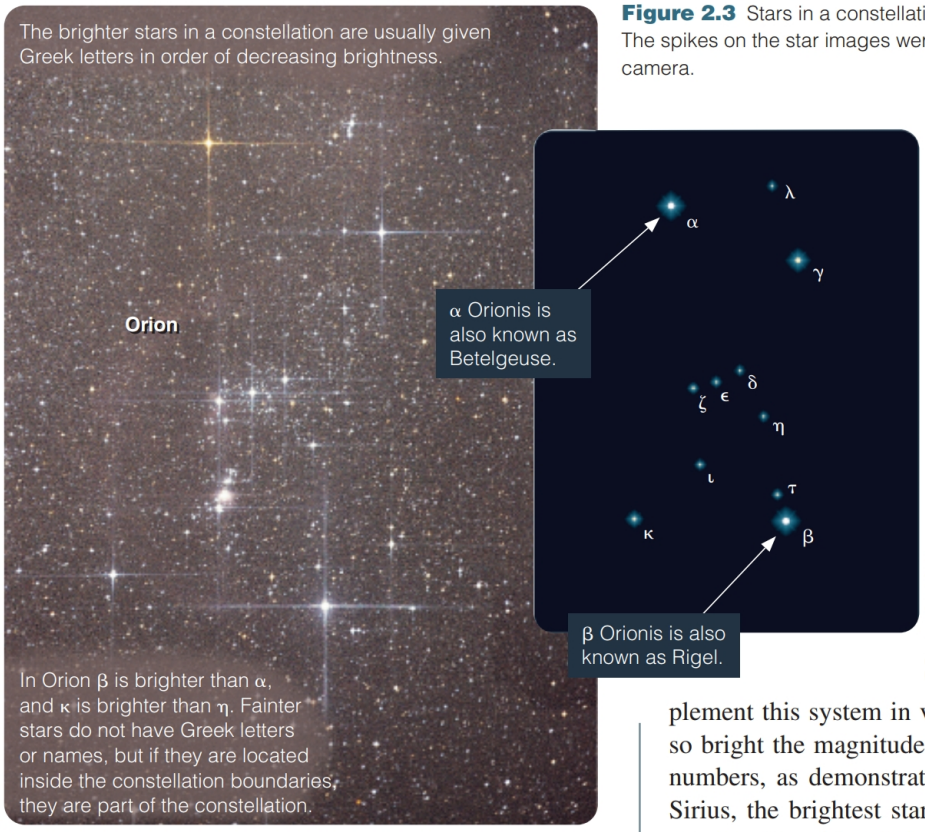


Figure 2.3 Stars in a constellation can be identified by Greek letters. The spikes on the star images were produced by the optics of the camera.

apparent visual magnitude (m_V) A measure of the brightness of a star as seen by human eyes on Earth.

flux A measure of the flow of energy per time through a surface, usually applied to light.

than sixth-magnitude stars. This information made it possible to properly quantify the magnitude system using a logarithmic scale. (Refer to **Magnitudes** in the Math Reference Cards.) Stellar brightness expressed in this system is known as **apparent visual magnitude (m_V)**, describing how the star looks to human eyes observing from Earth.

Brightness is quite subjective, depending on both the physiology of eyes and the psychology of perception. To be scientifically accurate you should refer to **flux**—a measure of the light energy from a star that hits one square metre in one second. With modern scientific instruments astronomers can measure the flux of starlight with high precision and then use the simple mathematical relationship that relates light flux to apparent visual magnitude. Instead of saying that the star known by the charming name Chort (Theta Leonis) is about third magnitude, you can say its magnitude is 3.34. Consequently, precise modern measurements of the brightness of stars are still connected to observations of apparent visual magnitude that go back to the time of Hipparchus. Interestingly, Vega, the brightest star in the constellation Lyra (the Harp), has an apparent magnitude very close to zero and has been used as a reference point for the magnitude system.

Limitations of the apparent visual magnitude system have motivated astronomers to supplement this system in various ways: (1) Some stars are so bright the magnitude scale must extend into negative numbers, as demonstrated in Figure 2.4. On this scale, Sirius, the brightest star in the sky, has a magnitude of −1.47. (2) With a telescope you can find stars much fainter than the limit for your unaided eyes, so the magnitude system has also been extended to numbers larger than sixth magnitude to include faint stars. (3) Although some stars emit large amounts of infrared or ultraviolet light, those types of radiation (discussed further in Chapters 4 and 5) are invisible to human eyes. The subscript "V" in m_V is a reminder that you are counting only light that is visible. Other magnitude systems have been invented to express the brightness of invisible light arriving at Earth

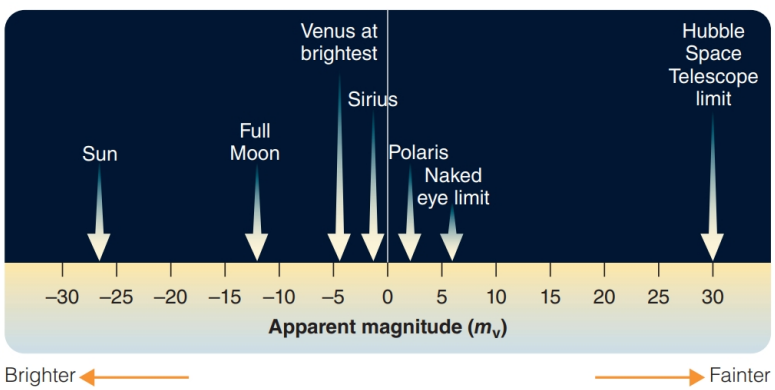


Figure 2.4 The scale of apparent visual magnitudes extends to negative numbers to represent the brightest objects and to positive numbers larger than 6 to represent objects fainter than the human eye can see.

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HOW DO WE KNOW? 2.1



Scientific Models

Frameworks for thinking about nature. A scientific model is a carefully devised mental conception of how something works, a framework that helps scientists think about some aspect of nature. For example, astronomers use the celestial sphere as a way to think about the motions of the sky, Sun, Moon, and stars.

Some models are imprecise—the psychologist's model of how the human mind processes visual information into images, for instance. But other models are so specific that they can be expressed as a set of mathematical equations, such as those used to describe how gas falls into a black hole. You could use metal and plastic to build a celestial globe, but the importance of a model is its use as a mental conception more than its physical presence.

A model is not meant to be a statement of truth. The celestial sphere



Vladimir Breytberg / Shutterstock.com

is not real; you know the stars are scattered through space at various distances. Nevertheless, you can imagine a celestial sphere and use it to help you think about the sky. A scientific model does not have to be true to be useful. Chemists, for example, think about the atoms in molecules by visualizing them as spheres joined together by sticks. This model of a molecule is not really correct, but it is a helpful way to think about molecules; it gives chemists a framework within which to organize their ideas.

Because scientific models are not meant to be totally correct, you must always remember the assumptions on which they are based. If you begin to think a model is true, it can mislead you instead of helping you. The celestial sphere, for instance, can help you think about the sky, but you must remember that the universe is much larger and more complex than this ancient scientific model of the heavens.

from the stars. (4) An apparent magnitude tells only how bright the star is as seen from Earth but doesn't tell anything about a star's true power output because the star's distance is not included. You can describe the true power output of stars with another magnitude system that will be described in Chapter 6.

2.2 The Sky and Its Motions

As mentioned earlier in this chapter, the sky appears as a beautiful blue dome in the daytime but a perplexing array of pinpoints of lights at night. Learning to understand the motion of the various objects dominating the sky requires that you first understand the perspectives of people who observed the sky thousands of years ago.

The Celestial Sphere

Early astronomers viewed the sky as a great sphere of very large radius surrounding Earth with the stars pinned to the inside of the dome. Modern astronomers know that the stars and nebulae are scattered through space at different distances, but it is still convenient and useful in some contexts for you to think of the sky as a great sphere enclosing Earth, with all stars at one distance. The **celestial sphere** is an example of a **scientific model**, a common feature of scientific thought (see **How Do We Know? 2.1**). You will learn about many scientific models in the chapters that follow.

As you study **Visualizing Astronomy 2.1, The Sky Around Us**, notice three important points:

celestial sphere An imaginary sphere of very large radius surrounding Earth to which the planets, stars, Sun, and Moon seem to be attached.

scientific model A concept that helps one think about some aspect of nature, but is not necessarily true.

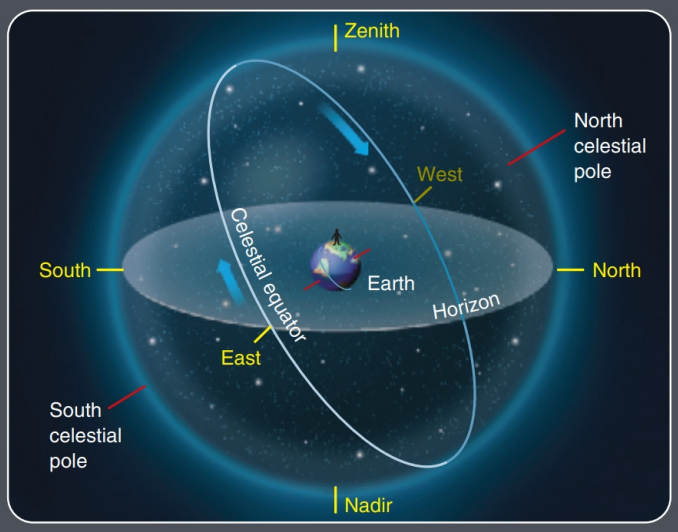
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Visualizing Astronomy 2.1
THE SKY AROUND US

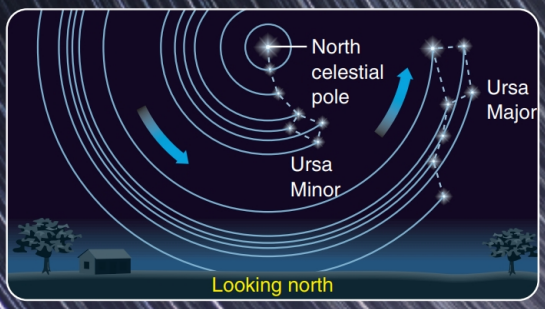
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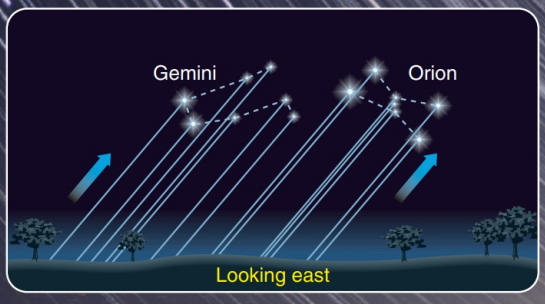
The eastward rotation of Earth causes the Sun, Moon, and stars to move westward in the sky as if the **celestial sphere** were rotating westward around Earth. From any location on Earth you see only half of the celestial sphere, the half above the **horizon**. The **zenith** marks the top of the sky above your head, and the **nadir** marks the bottom of the sky directly under your feet. The drawing at right shows the view for an observer in North America. An observer in South America would have a dramatically different horizon, zenith, and nadir.

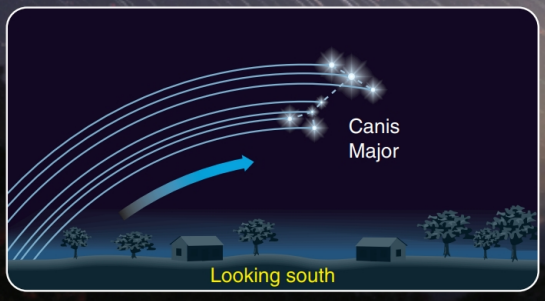
The apparent pivot points are the **north celestial pole** and the **south celestial pole** located directly above Earth's north and south poles. Halfway between the celestial poles lies the **celestial equator**. Earth's rotation defines the directions you use every day. The **north point** and **south point** are the points on the horizon closest to the celestial poles. The **east point** and the **west point** lie halfway between the north and south points. The celestial equator always touches the horizon at the east and west points.



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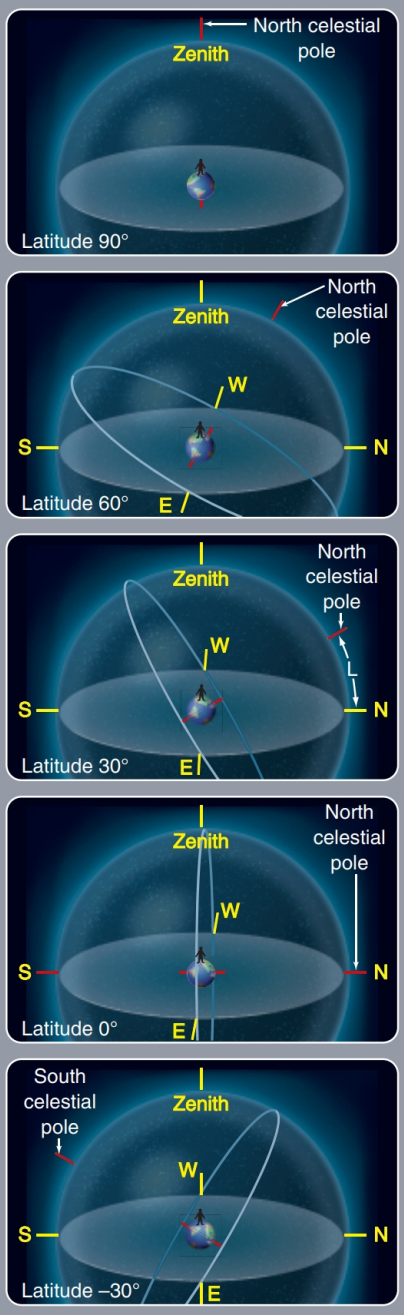


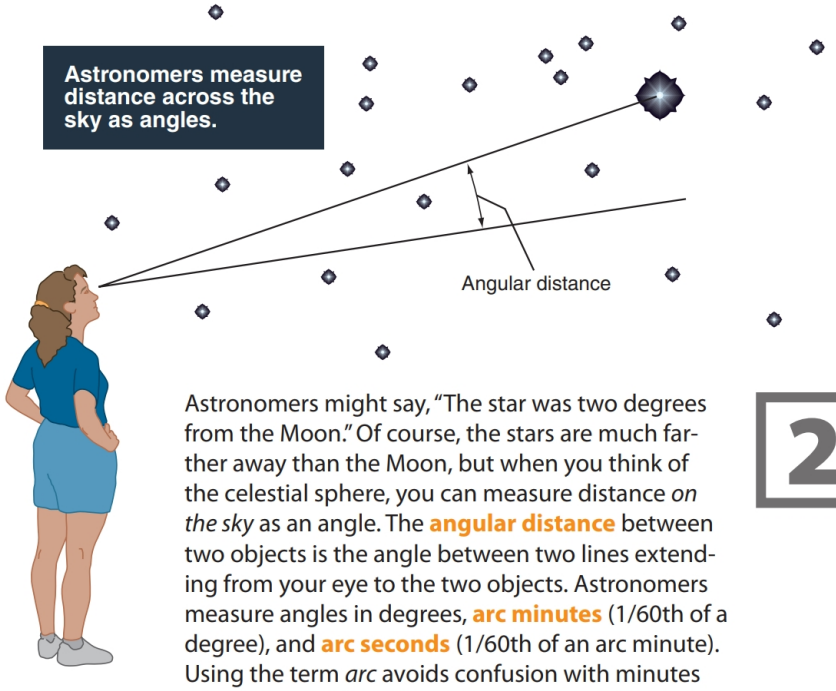
1a

This time exposure of about 30 minutes shows stars as streaks, called star trails, rising behind an observatory dome. The camera was facing northeast to take this photo. The motion you see in the sky depends on which direction you look, as shown at right. Looking north, you see the star Polaris, the North Star, located near the north celestial pole. As the sky appears to rotate westward, Polaris hardly moves but other stars circle the celestial pole. Looking south from a location in North America you can see stars circling the south celestial pole, which is invisible below the southern horizon.

P. Marenfeld & NOAO/AURA/NSF

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2

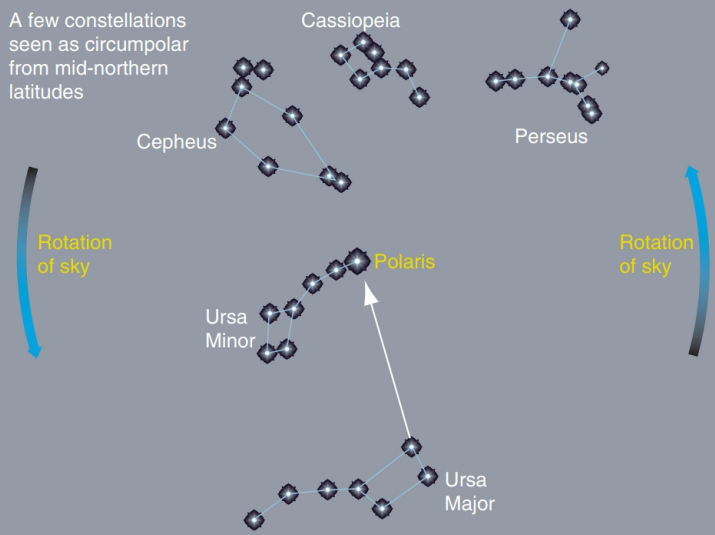
Astronomers might say, "The star was two degrees from the Moon." Of course, the stars are much farther away than the Moon, but when you think of the celestial sphere, you can measure distance *on the sky* as an angle. The **angular distance** between two objects is the angle between two lines extending from your eye to the two objects. Astronomers measure angles in degrees, **arc minutes** (1/60th of a degree), and **arc seconds** (1/60th of an arc minute). Using the term *arc* avoids confusion with minutes and seconds of time. The **angular diameter** of an object is the angular distance from one edge to the other. The Sun and Moon are each about half a degree in diameter, and the bowl of the Big Dipper is about 10 degrees wide.

3

What you see in the sky depends on your latitude as shown at left. Imagine that you begin a journey in the ice and snow at Earth's North Pole with the north celestial pole directly overhead. As you walk southward, the celestial pole moves toward the horizon, and you can see farther into the southern sky. The angular distance from the horizon to the north celestial pole always equals your latitude (L)—the basis for celestial navigation. As you cross Earth's equator, the celestial equator would pass through your zenith, and the north celestial pole would sink below your northern horizon.

3a

Circumpolar constellations are those that never rise or set. From mid-northern latitudes, as shown at right, you see a number of familiar constellations circling Polaris and never dipping below the horizon. As the sky rotates, the pointer stars at the front of the Big Dipper always point toward Polaris. Circumpolar constellations near the south celestial pole never rise when seen from mid-northern latitudes. From a high latitude such as Norway, you would have more circumpolar constellations, and from Quito, Ecuador, located on Earth's equator, you would have no circumpolar constellations at all.



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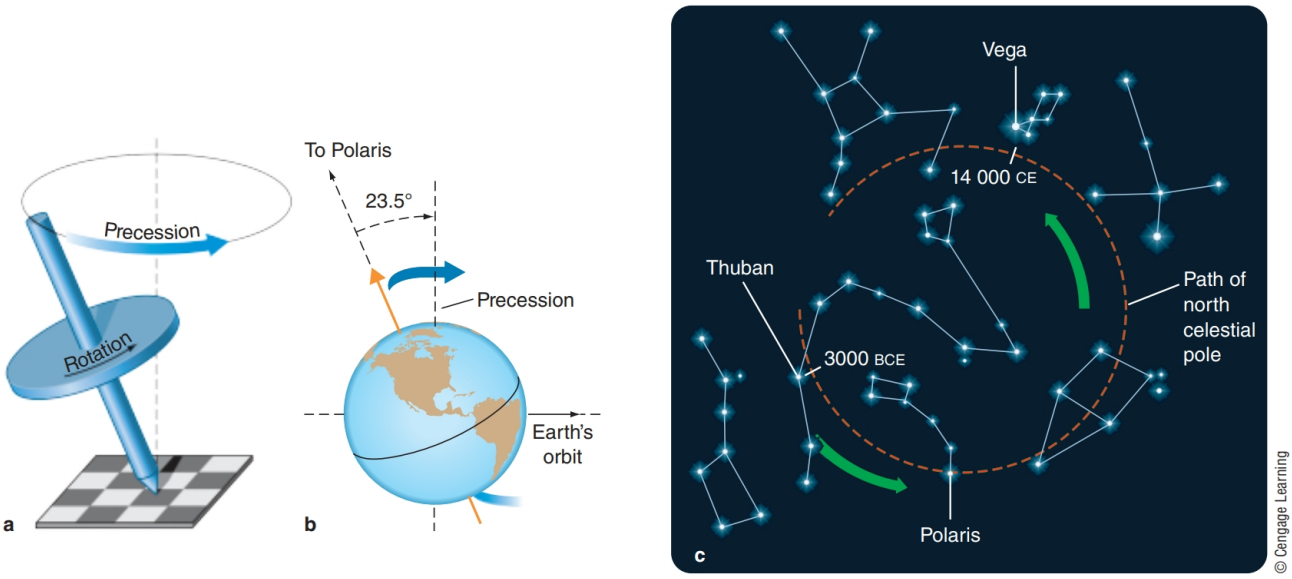


Figure 2.5 Precession. (a) A spinning top precesses in a slow circular motion around the perpendicular to the floor because its weight tends to make it fall over. (b) Earth precesses around the perpendicular to its orbit because the gravity of the Sun and Moon tend to twist it "upright." (c) Precession causes the north celestial pole to drift among the stars, completing a circle in about 26 000 years.

1. Objects in the sky appear to rotate westward around Earth each day (they rise in the east and set in the west), but that is a consequence of the eastward rotation of Earth. This produces day and night.
2. What you can see of the sky depends on where you are on Earth. For example, Australians see many constellations and asterisms not visible from North America, but they never see the Big Dipper. Canadians see asterisms and constellations rotate around the North Star in concentric circles.
3. Astronomers measure distances across the sky as angles expressed in units of degrees and subdivisions of degrees called arc minutes and arc seconds.

Precession

One part of Earth's motion that is not obvious to amateur astronomers is the subtle change in the orientation of Earth's rotational axis, because such change can be detected only over centuries. More than 2000 years ago Hipparchus compared a few of his star positions with those made by other astronomers nearly two centuries before him and realized that the celestial poles and equator were slowly moving relative to the stars. Eventually astronomers understood that this apparent motion is caused by a special motion of Earth called **precession**.

precession The slow change in orientation of Earth's axis of rotation. One cycle takes nearly 26 000 years.

If you have ever played with a toy top or gyroscope, you may have observed that the axis of such a rapidly spinning object sweeps around relatively slowly in a circle. Look at Figure 2.5 and think about how the top moves. The weight of the top tends to make it tip away from rotating about a vertical axis and this, combined with its rapid rotation, makes its axis sweep around slowly in precession motion.

Comparing Figure 2.5b to the motion of the top in Figure 2.5a, you can see that Earth spins like a giant top, but it does not spin upright relative to its orbit around the Sun. Instead, Earth's axis along with its equator is tipped 23.4 degrees from vertical. Earth's enormous mass and relatively rapid rotation keep its axis of rotation currently pointed toward a spot near the star Polaris (alpha Ursa Minoris), and its axis direction would not change if Earth were a perfect sphere. However, Earth has a slight bulge around its middle, and the gravity of the Sun and Moon both pull on this bulge, tending to twist Earth's axis upright relative to its orbit. The combination of these forces and Earth's rotation causes Earth's axis to precess in a slow circular sweep, taking about 26 000 years for one cycle and tracing out an imaginary cone over this time frame.

Because the celestial poles and equator are defined by Earth's rotational axis, precession moves these reference marks. Figure 2.5c shows the apparent path followed by the north celestial pole over thousands of years. You would notice no change at all from night to night or year to year, but precise measurements reveal their slow apparent motion. Over centuries,

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precession has dramatic effects. Egyptian records show that 4800 years ago the north celestial pole was near the star Thuban (alpha Draconis). The pole is now approaching Polaris and will be closest to it in about the year 2100. In another 12 000 years the pole will have moved to the vicinity of the very bright star Vega (alpha Lyrae).

2.3 The Cycle of the Sun

Before learning about the apparent motion of the Sun it is important that you understand two important terms regarding circular motion. The first term involves **rotation**, defined as the turning of a body on its axis. Every object in the universe appears to rotate or spin in space, along with any other motion it may have, whether it be Earth, the Sun, the planets, the asteroids, or even our own Milky Way galaxy. Earth rotates on its axis, and this produces day and night. On the other hand, the term **revolution** means the motion of a body around a point outside the body. Earth also revolves around the Sun, and that produces the yearly cycle.

The Annual Motion of the Sun

You are very familiar with the apparent daily motion of the Sun, and you know that it is due to the rotation of Earth. Even in the daytime the sky is actually filled with stars, but you can't see them because the glare of sunlight fills our atmosphere with scattered light, and you can see only the brilliant blue sky. If the Sun were fainter and you could see the stars in the daytime, you would notice that the Sun appears to be moving slowly eastward relative to the background of the distant stars. This apparent motion is caused by the orbital motion, or revolution, of Earth around the Sun. In January you would see the Sun in front of the constellation Sagittarius. By March you would see the Sun in front of Aquarius. Note that your angle of view in Figure 2.6 makes Earth's orbit seem very elliptical when it is really almost a perfect circle.

rotation Motion around an axis passing through the rotating body.

revolution Orbital motion about a point located outside the orbiting body.

ecliptic The apparent path of the Sun around the sky.

Through the year, the Sun moves eastward among the stars following a line called the **ecliptic**, the apparent path of the Sun among the stars. As this is a difficult concept to visualize you should recall the concept of the celestial sphere; if the sky were a great screen, the ecliptic would be the shadow cast by Earth's orbit. In other words, the ecliptic plane is that defined by Earth's orbit around the Sun. Earth orbits the Sun in 365.26 days, and consequently the Sun appears to go once around the sky in the same period. You don't notice this motion because you cannot see the stars in the daytime, but the apparent motion of the Sun caused by a real motion of Earth has an important consequence that you do notice—the seasons.

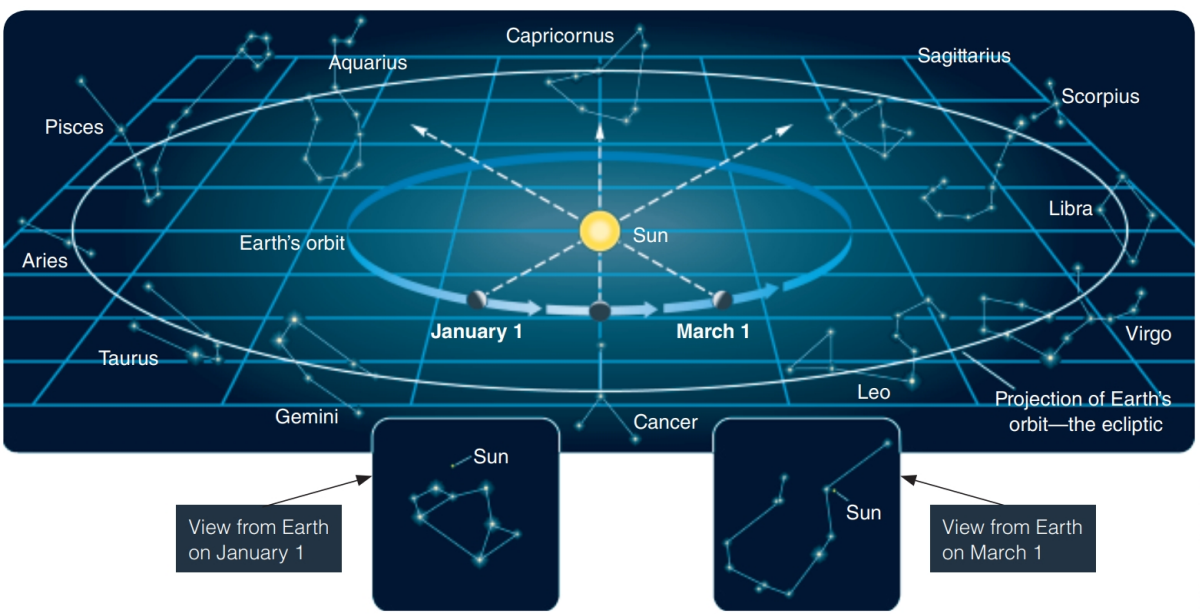


Figure 2.6 The motion of Earth around the Sun makes the Sun appear to move against the background of the stars. The circular orbit of Earth is thus projected on the sky as the ecliptic, the circular path of the Sun during the year as seen from Earth. If you could see the stars in the daytime, you would notice the Sun crossing in front of the distant constellations as Earth moves along its orbit.

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HOW DO WE KNOW? 2.2

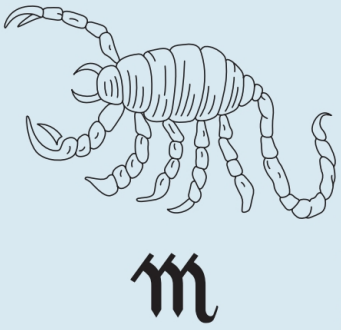


Pseudoscience

What is the difference between a science and a pseudoscience? Astronomers have a low opinion of beliefs such as astrology, mostly because they are groundless but also because they *pretend* to be a science. They are *pseudosciences*, from the Greek *pseudo*, meaning false.

A pseudoscience is a set of beliefs that appear to be based on scientific ideas but that fail to obey the most basic rules of science. For example, some years ago a claim was made that pyramidal shapes focus cosmic forces on anything underneath and might have healing properties. Supposedly, a pyramid made of paper, plastic, or other materials would preserve fruit, sharpen razor blades, and do other miraculous things. Many books promoted the idea of the special power of pyramids, and this idea led to a popular fad.

A key characteristic of science is that its claims can be tested and verified. In this case, simple experiments showed that any shape, not just a pyramid, protects a piece of fruit from



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airborne spores and allows it to dry without rotting. Likewise, any shape allows oxidation to improve the cutting edge of a razor blade. Because experimental evidence contradicted the claim and because supporters of the theory declined to abandon or revise their claims, you can recognize pyramid power as a pseudoscience. Disregard of contradictory evidence and alternate explanations is a sure sign of a pseudoscience.

Pseudoscientific claims can be self-fulfilling. For example, some believers slept under pyramidal tents to improve their rest. There is no logical mechanism by which such a tent could affect a sleeper, but because people wanted and expected the claim to be true, they reported that they slept more soundly. Vague claims based on personal testimony that cannot be tested are another sign of a pseudoscience.

Astrology is probably the best known pseudoscience. It has been tested over and over for centuries, and it doesn't work: There is no connection between the positions of the Sun, Moon, and planets and people's personalities, or events in their lives. Nevertheless, many people believe in astrology despite contradictory evidence. Many pseudosciences appeal to our need to understand and control the world around us. Some such claims involve medical cures, ranging from using magnetic bracelets and crystals to focus mystical power to astonishingly expensive, illegal, and dangerous treatments for cancer. Logic is a stranger to pseudoscience, but human fears and needs are not.

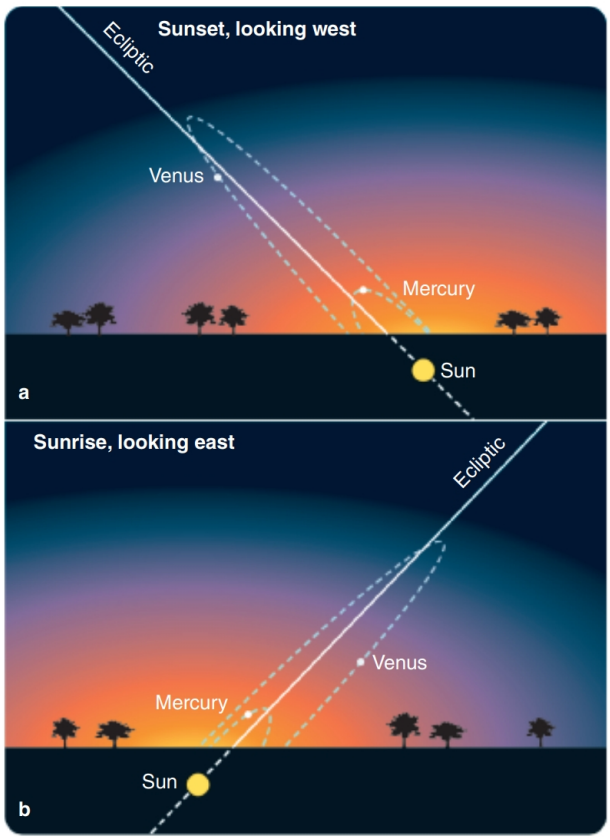
The Seasons

The seasons are caused by the revolution of Earth around the Sun, combined with a simple fact you have already encountered: Earth's rotational axis (and, consequently, its equator) is tipped 23.4 degrees relative to its orbit. Another way of stating this important fact is to realize that Earth's equatorial plane is tipped at 23.4 degrees to the ecliptic plane, as shown in **Visualizing Astronomy 2.2, The Cycle of the Seasons**, where two important principles are apparent:

1. The seasons are *not* caused by variation in the distance between Earth and the Sun. Earth's orbit is almost circular, so it is always about the same distance from the Sun.
2. The seasons *are* caused by changes in the amount of solar energy that Earth's northern and southern hemispheres receive at different times of the year, which results from the tip of Earth's equator and axis relative to its orbit.

Because the seasons are very important as a cycle of growth and harvest, cultures around the world have attached great significance to the ecliptic. It marks the centre line of the zodiac ("circle of animals"), and the motion of the Sun, Moon, and the five visible planets (Mercury, Venus, Mars, Jupiter, and Saturn) are the basis of the ancient superstition of astrology (see **How Do We Know? 2.2**). The signs of the zodiac are no longer important in astronomy. You can look for

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Figure 2.7 Mercury and Venus follow orbits that keep them near the Sun, and they are visible only soon after sunset or just before sunrise. Venus takes 584 days to move from morning sky to evening sky and back again, but Mercury zips around in only 116 days.

the planets along the ecliptic appearing as if they were bright stars. Mars looks quite orange in colour. Venus and Mercury orbit inside Earth's orbit, so they never get far from the Sun and are visible in the west after sunset or in the east before sunrise, as you can see in Figure 2.7. Venus can be very bright, but Mercury is often difficult to see near the horizon. By tradition, any planet in the sunset sky is called an evening star, and any planet in the dawn sky is called a morning star. Perhaps the most beautiful is Venus, which can become as bright as magnitude –4.7. As Venus moves around its orbit, it can dominate the western sky each evening for many weeks, but eventually its orbit appears to carry it back toward the Sun, as seen from Earth, and it is lost in the haze near the horizon. A few weeks later you can see Venus reappear in the dawn sky as a brilliant morning star. Months later it will switch back to being an evening star again.

2.4 The Cycles of the Moon

Along with the Sun, the Moon is an important object in our sky. You are familiar with the Moon as a nighttime body but you might not realize that it can be readily seen during daytime. The Moon orbits eastward around Earth about once a month. Starting this evening, look for the Moon in the sky. If it is a cloudy night or if the Moon is in the wrong part of its orbit you will not see it, but keep trying on successive evenings and within a week or two you will see the Moon. Then watch for the Moon on following evenings, and you will see it move along its orbit around Earth and cycling through its phases as it has done for some billions of years.

The Motion of the Moon

If you watch the Moon night after night, you will notice two things about its motion. First, you will see it moving relative to the background of stars; second, you will notice that the markings on its face don't change. These two observations can help you understand the motion of the Moon and the origin of the Moon's phases.

The Moon moves rapidly among the constellations. If you watch the Moon for just an hour, you can see it move eastward against the background of stars by slightly more than its own apparent diameter. Each night when you look at the Moon, you will see it is roughly half the width of a zodiac constellation (about 13 degrees) to the east of its location the night before. This movement is the result of the motion of the Moon along its orbit around Earth.

The Cycle of Moon Phases

The changing shape of the illuminated part of the Moon as it orbits Earth is one of the most easily observed phenomena in astronomy. You have surely seen the full Moon rising dramatically or a thin crescent moon hanging in the evening sky. If you carefully study **Visualizing Astronomy 2.3, The Phases of the Moon** you will notice three important points:

1. The Moon always keeps the same side facing Earth, and you never see the far side of the Moon. This is because the Moon is tidally or gravitationally locked to Earth resulting in a motion known as synchronous rotation. "The man in the Moon" (some cultures see "the rabbit in the Moon" instead) is produced by familiar features on the Moon's near side.

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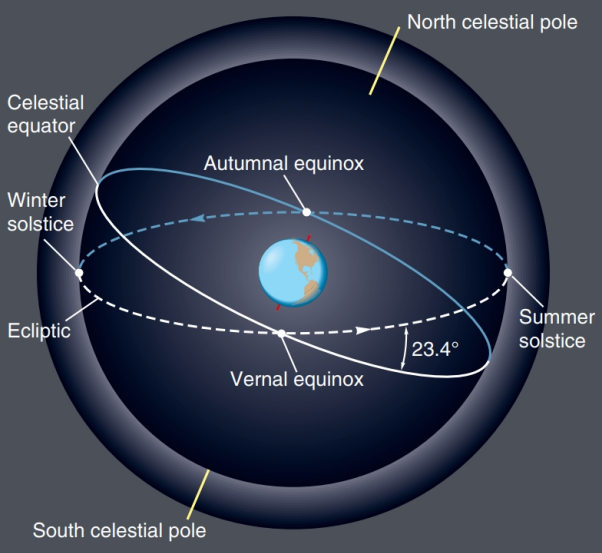
Visualizing Astronomy 2.2

THE CYCLE OF THE SEASONS

1

You can use the celestial sphere to help you think about the seasons. The celestial equator is the projection of Earth's equator on the sky, and the ecliptic is the projection of Earth's orbit on the sky. Because Earth is tipped in its orbit, the ecliptic and equator are inclined to each other by 23.4 degrees, as shown at right. As the Sun moves eastward around the sky, it spends half the year in the southern half of the sky and half the year in the northern half. That causes the seasons.

The Sun crosses the celestial equator going northward at the point called the **vernal equinox**. The Sun is at its farthest north at the point called the **summer solstice**. It crosses the celestial equator going southward at the **autumnal equinox** and reaches its most southern point at the **winter solstice**.



Event	Date*	N. Hemisphere
Vernal equinox	March 20	Spring begins
Summer solstice	June 22	Summer begins
Autumnal equinox	September 22	Autumn begins
Winter solstice	December 21	Winter begins

* Give or take a day due to leap years and other factors.

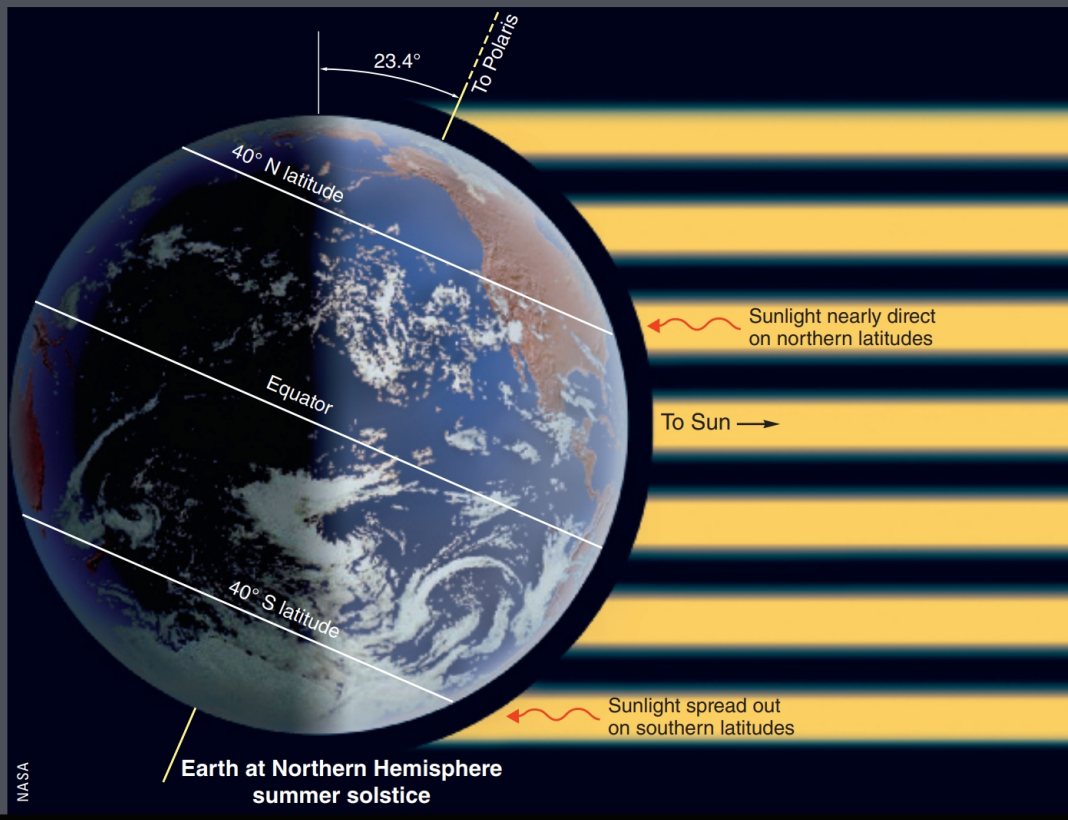
1a

The seasons are defined by the dates when the Sun crosses these four points, as shown in the table at the right. *Equinox* comes from the word for "equal"; the day of an equinox has equal amounts of daylight and darkness. *Solstice* comes from the words meaning "Sun" and "stationary." *Vernal* comes from the word for "green." The "green" equinox marks the beginning of spring in the Northern Hemisphere.

1b

On the day of the summer solstice in late June, Earth's Northern Hemisphere is inclined toward the Sun, and sunlight shines almost straight down at northern latitudes. At southern latitudes, sunlight strikes the ground at an angle and spreads out. North America has warm weather, and South America has cool weather.

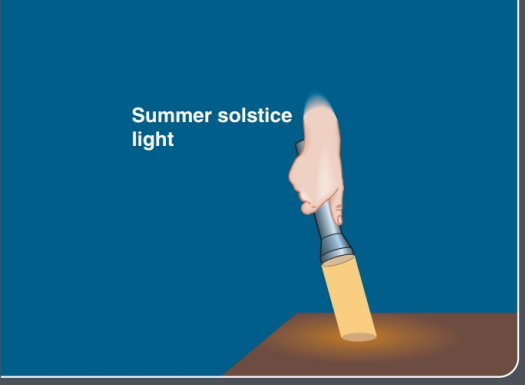
Earth's axis of rotation points toward Polaris, and, like a top, the spinning Earth holds its axis fixed as it orbits the Sun. On one side of the Sun, Earth's Northern Hemisphere leans toward the Sun; on the other side of its orbit, it leans away. However, the direction of the axis of rotation does not change in the course of a year.



NASA

Earth at Northern Hemisphere summer solstice

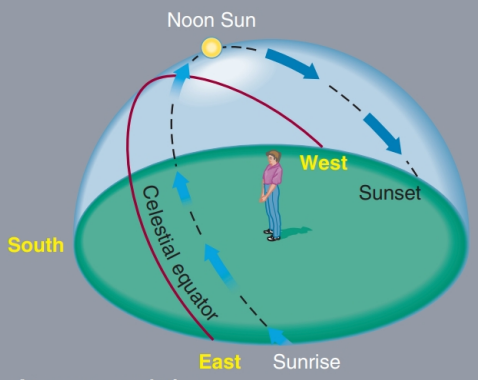
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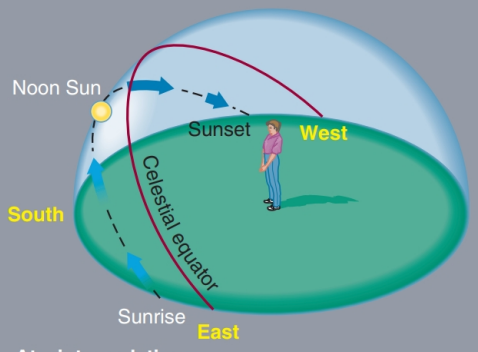
1c Light striking the ground at a steep angle spreads out less than light striking the ground at a shallow angle. Light from the summer solstice Sun strikes northern latitudes from nearly overhead and is concentrated.



Light from the winter solstice Sun strikes northern latitudes at a much steeper angle and spreads out. The same amount of energy is spread over a larger area, so the ground receives less energy from the winter Sun.

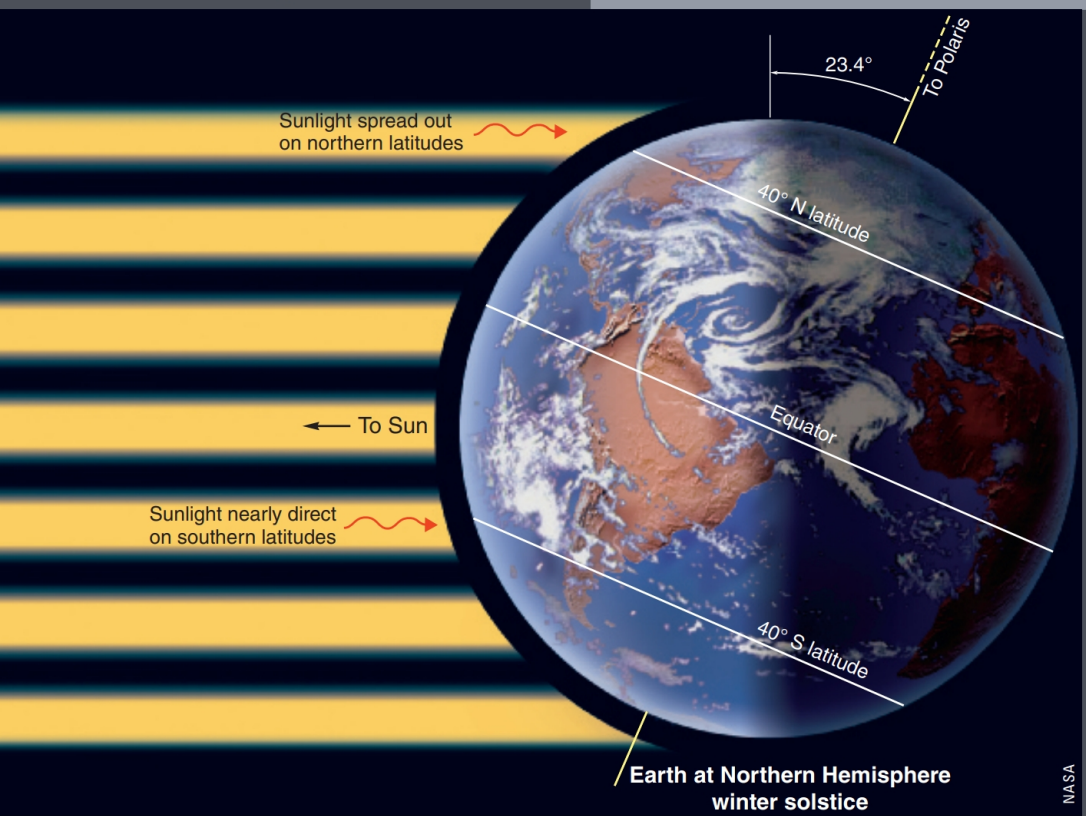


At summer solstice



At winter solstice

2 The two causes of the seasons are shown at right for someone in the Northern Hemisphere. First, the noon summer Sun is higher in the sky and the winter Sun is lower, as shown by the longer winter shadows. Thus winter sunlight is more spread out. Second, the summer Sun rises in the northeast and sets in the northwest, spending more than 12 hours in the sky. The winter Sun rises in the southeast and sets in the southwest, spending less than 12 hours in the sky. Both of these effects mean that northern latitudes receive more energy from the summer Sun, and summer days are warmer than winter days.



Earth at Northern Hemisphere winter solstice

NASA

1d On the day of the winter solstice in late December, Earth's Northern Hemisphere is inclined away from the Sun, and sunlight strikes the ground at an angle and spreads out. At southern latitudes, sunlight shines almost straight down and does not spread out. North America has cool weather and South America has warm weather.

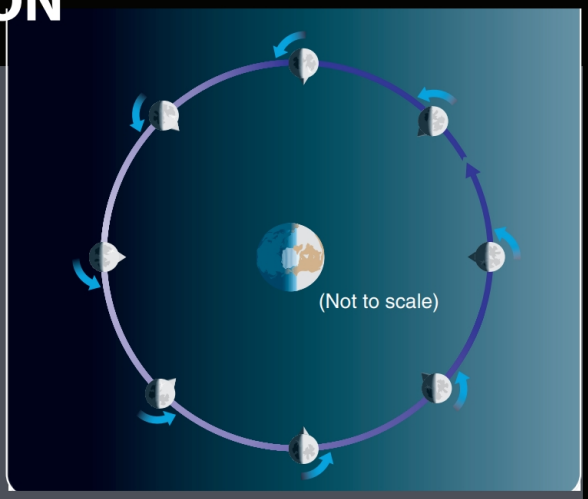
Earth's orbit is only very slightly elliptical. About January 3, Earth is at **perihelion**, its closest point to the Sun, when it is only 1.7 percent closer than average. About July 5, Earth is at **aphelion**, its most distant point from the Sun, when it is only 1.7 percent farther than average. This small variation does not significantly affect the seasons.

Visualizing Astronomy 2.3

THE PHASES OF THE MOON

1

As the Moon orbits Earth, it rotates to keep the same side facing Earth as shown at right. Consequently you always see the same features on the Moon, and you never see the far side of the Moon. A mountain on the Moon that points at Earth will always point at Earth as the Moon revolves and rotates.



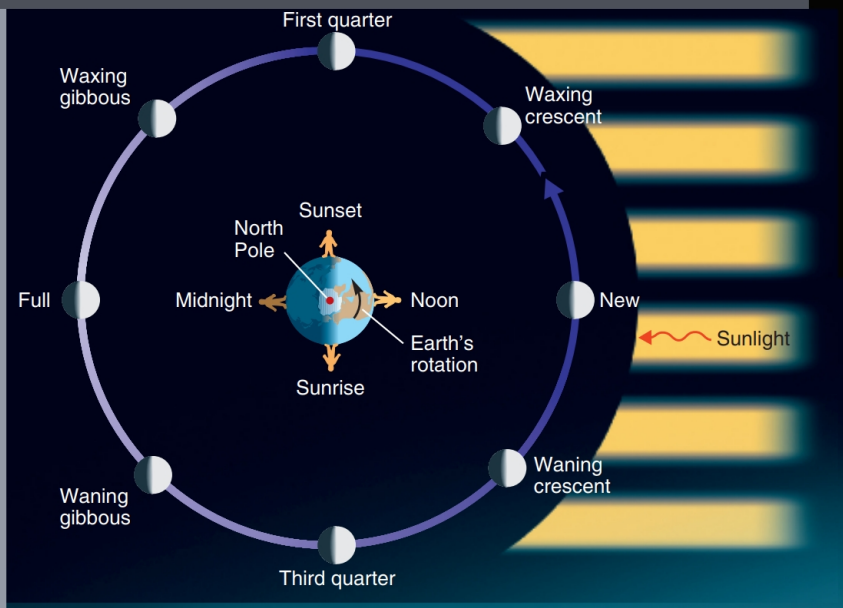
2

As seen at left, sunlight always illuminates half of the Moon. Because you see different amounts of this sunlit side, you see the Moon cycle through phases. At the phase called "new moon," sunlight illuminates the far side of the Moon, and the side you see is in darkness. At new moon, you can't see the Moon at all. At full moon, the side you see is fully lit, and the far side is in darkness. How much you see depends on where the Moon is in its orbit.

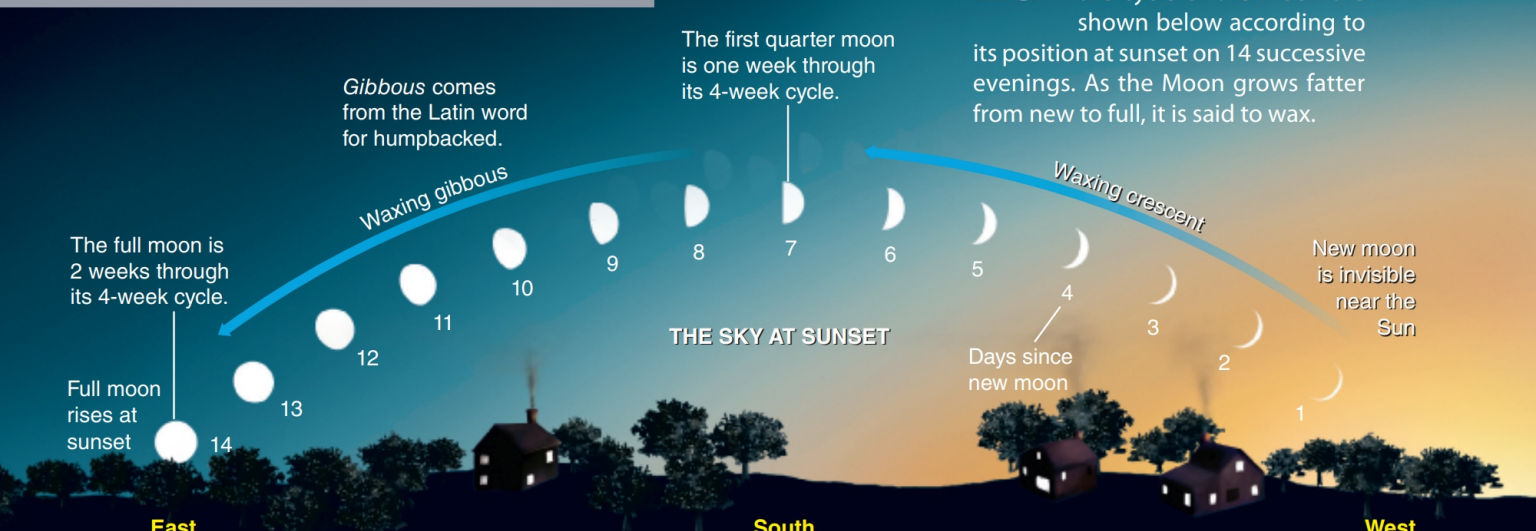
Notice that there is no such thing as the "dark side of the Moon." All parts of the Moon experience day and night in a monthlong cycle.

In the diagram at the right, you see that the new moon is close to the Sun in the sky, and the full moon is opposite the Sun. The time of day depends on the observer's location on Earth.

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2a The first two weeks of the cycle of the Moon are shown below according to its position at sunset on 14 successive evenings. As the Moon grows fatter from new to full, it is said to wax.



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3

The Moon orbits eastward around Earth in 27.32 days, its **sidereal period** (pronounced sy-deer-ial). This is how long the Moon takes to circle the sky once and return to the same position among the stars.

A complete cycle of lunar phases takes 29.53 days, the Moon's **synodic period**. (*Synodic* comes from the Greek words for "together" and "path.")

To see why the synodic period is longer than the sidereal period, study the star charts at the left.

Although you think of the lunar cycle as being about 4 weeks long, it is actually 1.53 days longer than 4 weeks. The calendar divides the year into 30-day periods called months (literally "moonths") in recognition of the 29.53-day synodic cycle of the Moon.

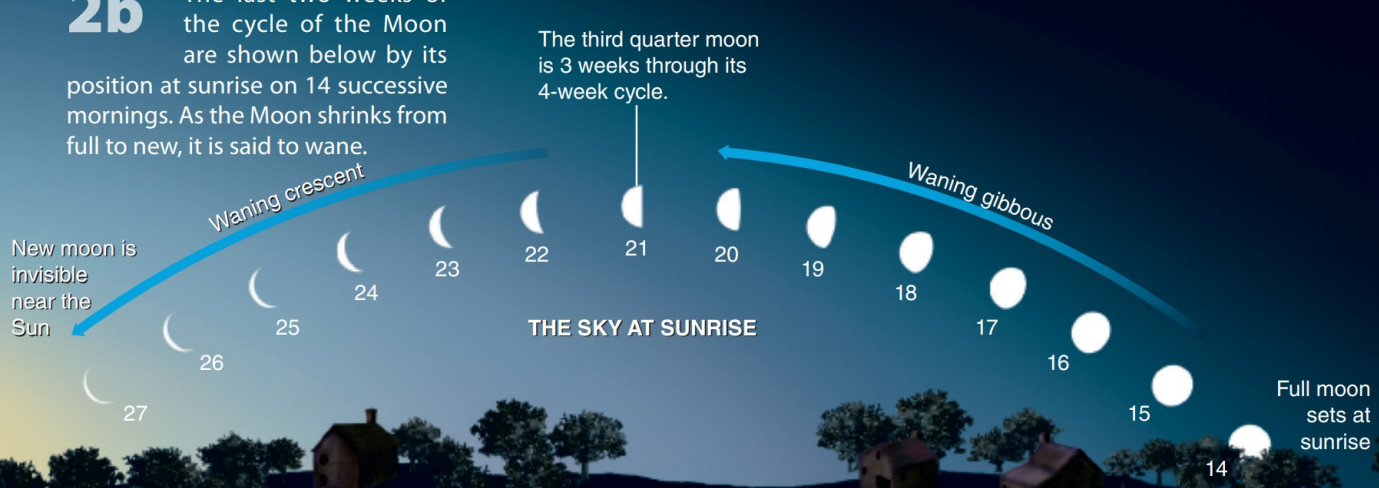
To think about the changing phases of the Moon, imagine facing the southern sky, which is where people living in the Northern Hemisphere find the ecliptic. The Moon crosses from west to east night by night, following the ecliptic.

You can use the diagram on the opposite page to determine when the Moon rises and sets at different phases.

TIMES OF MOONRISE AND MOONSET

Phase	Moonrise	Moonset
New	Dawn	Sunset
First quarter	Noon	Midnight
Full	Sunset	Dawn
Third quarter	Midnight	Noon

2b The last two weeks of the cycle of the Moon are shown below by its position at sunrise on 14 successive mornings. As the Moon shrinks from full to new, it is said to wane.



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Figure 2.8 In this sequence of lunar phases, the Moon shrinks from a thin crescent, to full, and back to a thin crescent. You see the same face of the Moon, the same mountains, craters, and plains, but the changing direction of sunlight produces the lunar phases.

2. The changing shape of the Moon as it passes through its cycle of phases is produced by sunlight illuminating different parts of the side of the Moon you can see. You always see the same side of the Moon looking down on you, but the shifting shadows make the "man in the Moon" change moods as the Moon cycles through its phases (see also Figure 2.8).
3. The orbital period of the Moon around Earth is not the same as the length of a Moon phase cycle. Although the length of the Moon's phase cycle is about 29.5 days, the sidereal month—the time needed for the Moon to return to the same place in the sky as measured by the stars—is 27.3 days. This difference is because of Earth's continuous motion around the Sun.

2.5 Eclipses

Eclipses occur because of a seemingly complicated combination of apparent motions of the Sun and Moon, yet they are easy to predict once all the cycles are understood, an understanding that dates back hundreds, if not thousands, of years. Eclipses are also among the most spectacular of nature's sights you will ever witness.

Solar Eclipses

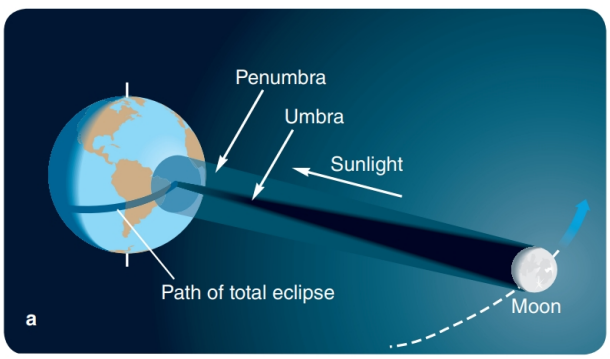
From Earth you can see a phenomenon that is not visible from most planets. The Sun is 400 times larger than our Moon and, on the average, 390 times farther away, so the Sun and Moon have nearly equal apparent diameters. (Refer to **The Small-Angle Formula** in the Math Reference Cards.) Thus, the Moon is just about the right size to cover the bright disk of the Sun and cause a **solar eclipse**. In a solar eclipse, the Sun is hidden (eclipsed) because the Moon is "in the way."

solar eclipse The event that occurs when the Moon passes directly between Earth and the Sun, blocking our view of the Sun.

umbra The region of a shadow that is totally shaded.

penumbra The portion of a shadow that is only partially shaded.

As you can see in Figure 2.9a the Moon casts a shadow that reaches all the way to part of Earth's surface, a shadow with two parts. The **umbra** is the region of total shadow. For example, if you were in the umbra of the Moon's shadow, you would see no portion of the Sun. The umbra of the Moon's shadow usually just barely reaches Earth's surface and covers a relatively small circular zone (Figure 2.9a). Standing in that umbral zone, you would be in total shadow, unable to see any part of the Sun's surface. That is called a total eclipse, as seen in Figure 2.9b. If you moved into the **penumbra**, however, you would



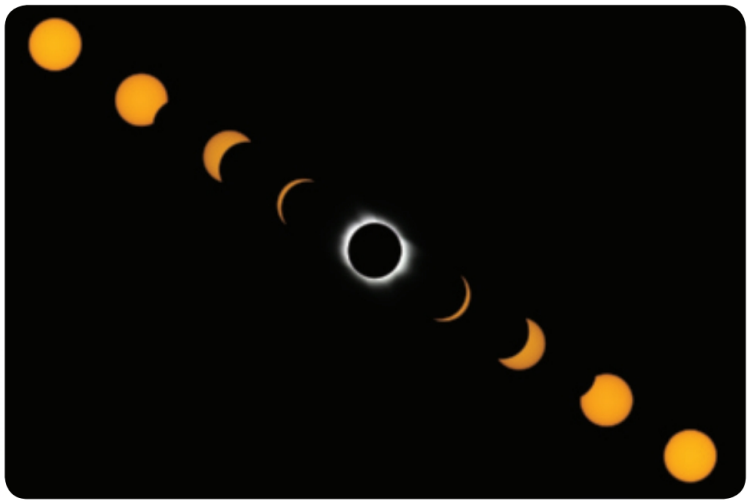
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Daniel Good

Figure 2.9 (a) The umbral shadow of the Moon sweeps over a narrow strip of Earth during a solar eclipse. (b) From a location inside the umbral shadow, you would see the Moon cover the bright surface of the Sun in a total solar eclipse. Note faint features of the Sun's atmosphere around the edge of the Moon's disk.

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Figure 2.10 Solar eclipse. The Moon moving from the right just begins to cross in front of the Sun. The disk of the Moon gradually covers the disk of the Sun. Sunlight begins to dim as more of the Sun's disk is covered. During totality, faint features of the atmosphere are often visible. A longer-exposure photograph during totality shows the extended solar atmosphere.

be in partial shadow but could also see part of the Sun peeking around the edge of the Moon. This is called a partial eclipse. Of course, if you are outside the penumbra, you see no eclipse at all.

Because of the orbital motion of the Moon and the rotation of Earth, the Moon's shadow sweeps rapidly across Earth in a long, narrow path of totality. If you want to see a total solar eclipse, you must be in the path of totality. When the umbra of the Moon's shadow sweeps over you, you see one of the most dramatic sights in the sky—the totally eclipsed Sun (Figure 2.10).

The eclipse begins as the Moon slowly crosses in front of the Sun. It takes about an hour for the Moon to cover the solar disk, but as the last sliver of Sun disappears, darkness arrives in a few seconds. Automatic streetlights come on, drivers turn on their car's headlights, and birds go to roost. The sky usually becomes so dark you can even see the brighter stars. The darkness lasts only a few minutes because the umbra is never more than 270 km in diameter on the surface of Earth and sweeps across the landscape at over 1600 km/hr. On average, the period of totality lasts only two or three minutes and never more than 7.5 minutes. During totality you can see subtle features of the Sun's atmosphere, such as red flamelike projections that are visible only during these moments when the brilliant disk of the Sun is completely covered by the Moon. (The Sun's atmosphere is discussed in more detail in Chapter 5.) As soon as part of the Sun's disk reappears, the fainter features vanish in the glare, and the period of totality is over. The Moon moves on in its orbit, and in an hour the Sun is completely visible again.

The Moon's orbit around Earth is slightly eccentric, having a perigee (closest distance) of 356.4 km and an apogee (farthest distance) of 406.7 km. When the Moon is near apogee its apparent size is smaller than that of the Sun and, thus, too small to completely cover the Sun. In this case, you see an **annular eclipse** that is a solar eclipse in which an annulus (meaning "ring") of the Sun's disk is visible around the disk of the Moon. The eclipse never becomes total; it never quite gets dark, and you can't see the faint features of the solar atmosphere. Additionally, Earth's orbit is slightly elliptical, so the Earth-to-Sun distance varies slightly, and so does the apparent diameter of the solar disk, contributing to the effect of the Moon's varying apparent size.

If you plan to observe a solar eclipse, it is very important to remember that the Sun is bright enough to burn your eyes and cause permanent damage if you look at it directly. This is true whether there is an eclipse or not. Solar eclipses can be misleading, tempting you to look at the Sun in spite of its brilliance and risking your eyesight.

During the few minutes of totality, the brilliant disk of the Sun is hidden and it is safe to look at the eclipse, but the partial eclipse phases and annular eclipses can be dangerous. See Figure 2.11 for a safe way to observe the partially eclipsed Sun. Table 2.1 provides information that helps you determine when some upcoming solar eclipses will be visible from your location.

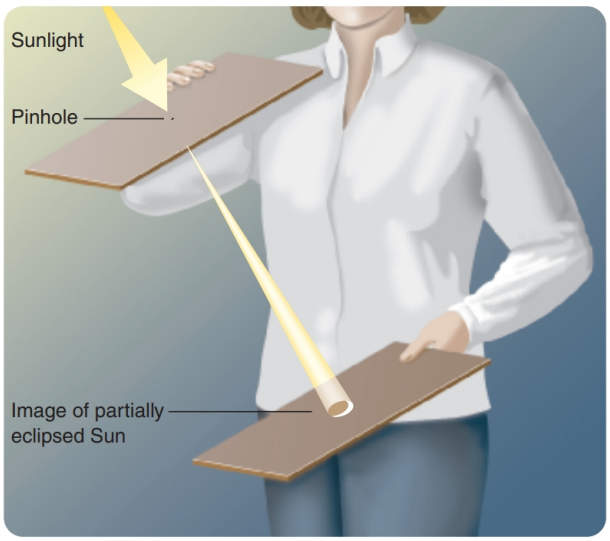
Lunar Eclipses

Occasionally, you can see the Moon darken and turn copper-red in a **lunar eclipse**. A lunar eclipse occurs only at full moon when the Moon moves through the shadow of Earth. Because the Moon shines by reflected sunlight, you see the Moon gradually darken as it enters the shadow. If you were on the Moon and in the umbra of Earth's shadow, you would see no portion of the Sun. If you moved into the penumbra, however, you would be in partial shadow and would see part

annular eclipse A solar eclipse in which the solar photosphere appears around the edge of the Moon in a bright ring, or annulus. Features of the solar atmosphere cannot be seen during an annular eclipse.

lunar eclipse The darkening of the Moon when it moves through Earth's shadow.

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Figure 2.11 A safe way to view the partial phases of a solar eclipse. Use a pinhole in a card to project an image of the Sun on a second card. The greater the distance between the cards, the larger (and fainter) the image will be.

of the Sun peeking around the edge of Earth, so the sunlight would be dimmed but not extinguished. You will recall that this is exactly the same when you are on Earth observing a solar eclipse. In a lunar eclipse, the Moon is hidden in Earth's shadow, and Earth is "in the way" of the sunlight.

If the orbit of the Moon carries it through the umbra of Earth's shadow, you see a total lunar eclipse, as demonstrated in Figure 2.12a. As you watch the Moon in the sky, it first moves into the penumbra and dims slightly; the deeper it moves into the penumbra, the more it dims. In about an hour, the Moon reaches the umbra, and you see the umbral shadow darken part of the Moon. It takes about an hour for the Moon to enter the umbra completely and become totally eclipsed. The period of total eclipse may last as long as 1 hour 45 minutes, though the timing of the eclipse depends on where the Moon crosses the shadow.

When the Moon is totally eclipsed, it does not disappear completely. Although it receives no direct sunlight, the Moon in the umbra does receive some sunlight refracted (bent)

Table 2.1 | Total and Annular Eclipses of the Sun, 2019–2026*

Date	Total/ Annular (T/A)	Time of Mid-Eclipse** (GMT)	Maximum Length of Total or Annular Phase (Min:Sec)	Region of Visibility
2019 July 2	T	19:24	4:33	Pacific, South America
2019 December 26	A	05:19	3:39	Southeast Asia, Pacific
2020 June 21	A	06:41	0:38	Africa, Asia
2020 December 14	T	16:15	2:10	Southern South America
2021 June 10	A	10:43	3:51	North America, Europe, Asia
2021 December 4	T	07:35	1:54	Antarctica, South America
2023 April 20	A/T	04:18	1:16	Southeast Asia, Philippines, Australia
2023 October 14	A	18:00	5:17	South and Central America, Western USA
2024 April 8	T	18:18	4:28	North America, Mexico
2024 October 2	A	18:46	7:25	South America, Pacific
2026 February 17	A	12:13	2:20	Antarctica
2026 August 12	T	17:47	2:18	Arctic, Greenland, Iceland, Spain

*The next solar eclipse visible from anywhere in Canada will occur on June 10, 2021 and then only in northern Ontario; the next solar eclipse visible from the United States will occur on October 14, 2023. There will be no total or annular solar eclipses in 2022 or 2025.

**Times are Greenwich Mean Time. Subtract 4 hours for Atlantic Time, 5 hours for Eastern Standard Time, 6 hours for Central Standard Time, 7 hours for Mountain Standard Time, and 8 hours for Pacific Standard Time. For Daylight Savings Time, add 1 hour to Standard Time.

Fred Espenak, Solar Eclipses: 2011–2020, 2021–2030, from http://eclipse.gsfc.nasa.gov/SEdecade/SEdecade2011.html

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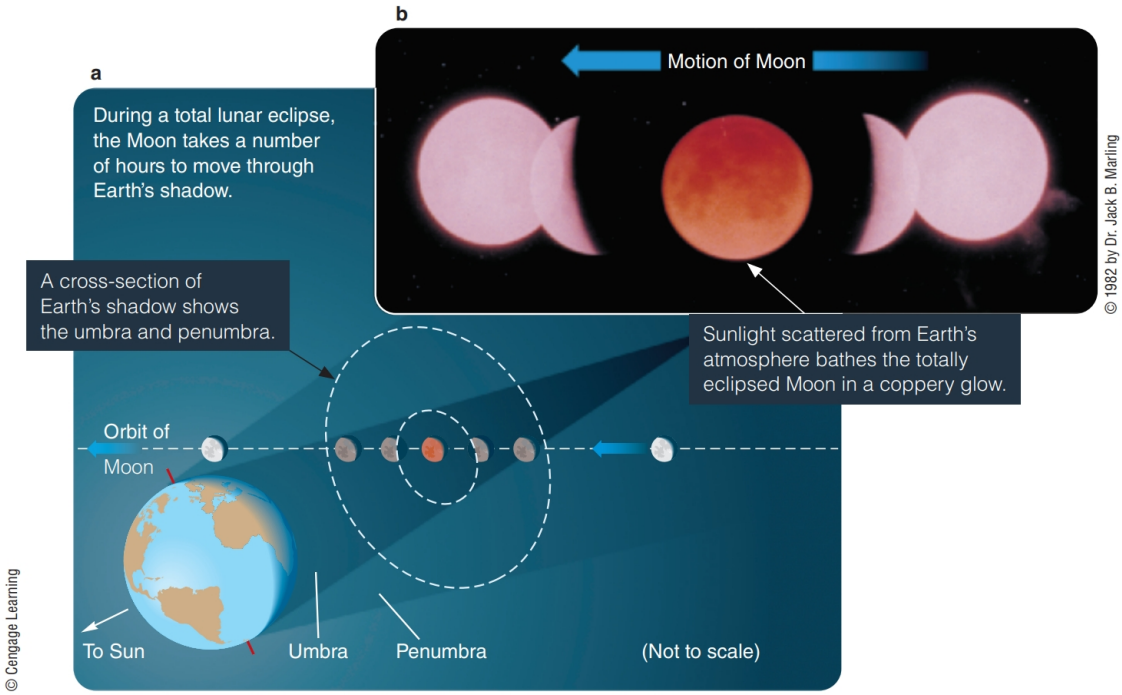


Figure 2.12 (a) Lunar eclipse. (b) From upper left to lower right, as the Moon passes through the shadow of Earth, sunlight from Earth's atmosphere bathes the totally eclipsed Moon in a coppery glow.

through Earth's atmosphere. If you were on the Moon during totality, you would not see any part of the Sun because it would be entirely hidden behind Earth. However, you would be able to see Earth's atmosphere illuminated from behind by the Sun. The red glow from this ring—consisting of all Earth's simultaneous sunsets and sunrises—illuminates the Moon during totality and makes it glow coppery red, as shown in Figure 2.12b.

If the Moon passes a bit too far north or south of the centre of Earth's shadow, it may only partially enter the umbra, and you see a partial lunar eclipse. The part of the Moon that remains outside the umbra in the penumbra receives some direct sunlight, and the glare is usually great enough to prevent us from seeing the faint coppery glow of the part of the Moon in the umbra.

Lunar eclipses always occur at full moon, but not at every full moon. The Moon's orbit is tipped about 5 degrees to the ecliptic, so most full moons cross the sky north or south of Earth's shadow, and there is no lunar eclipse that month (see Figure 2.13). For the same reason, solar eclipses always occur at new moon but not at every new moon. The orientation of the Moon's orbit in space varies slowly, and as a result, solar and lunar eclipses repeat in a pattern called the **Saros cycle**, lasting 18 years and 11⅓ days. Ancient peoples who understood the Saros cycle could predict eclipses without understanding what the Sun and Moon really were.

Saros cycle An 18-year, $11\frac{1}{3}$-day period, after which the pattern of lunar and solar eclipses repeats.

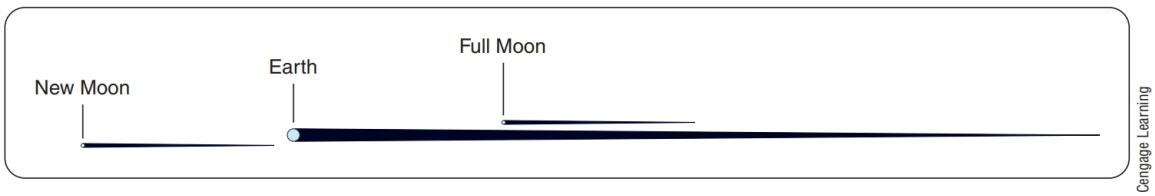


Figure 2.13 Umbral shadows of Earth and the Moon. Because of the tilt of the Moon's orbit relative to the ecliptic, it is easy for the shadows to miss their mark at full moon and at new moon and fail to produce eclipses. (The diameters of Earth and the Moon are exaggerated by a factor of 2 for clarity.)

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Table 2.2 Total and Partial Eclipses of the Moon, 2019–2026*

Date	Time of Mid-Eclipse (GMT)**	Length of Totality (Hr:Min)	Length of Eclipse (Hr:Min)
2019 July 16	21:32	Partial	2:58
2021 May 26	11:20	0:15	3:07
2021 November 19	09:04	Partial	3:28
2022 May 16	04:13	1:25	3:27
2022 November 8	11:00	1:25	3:40
2023 October 28	20:15	Partial	1:17
2024 September 18	02:45	Partial	1:03
2025 March 14	07:00	1:05	3:38
2025 September 7	18:13	1:22	3:29
2026 March 3	11:35	0:58	3:27
2026 August 28	04:14	Partial	3:18

*There are no total or partial lunar eclipses during 2016 or 2020.
**Times are Greenwich Mean Time. Subtract 4 hours for Atlantic Time, 4 hours for Atlantic Standard Time, 5 hours for Eastern Standard Time, 6 hours for Central Standard Time, 7 hours for Mountain Standard Time, and 8 hours for Pacific Standard Time. For Daylight Savings Time (mid-March through early November), add 1 hour to Standard Time. Lunar eclipses that occur between sunset and sunrise in your time zone will be visible, and those at midnight will be best placed.

Fred Espenak, Solar Eclipses: 2011–2020, 2021–2030, from http://eclipse.gsfc.nasa.gov/SEdecade/SEdecade2011.html

Although there are usually no more than one or two lunar eclipses each year, it is not difficult to see one. You need only be on the dark side of Earth when the Moon passes through Earth's shadow. That is, the eclipse must occur between sunset and sunrise at your location to be visible. Table 2.2 provides information for you to determine when some upcoming lunar eclipses will be visible.

2.6 Stellar Coordinates

Picture Earth hanging at the centre of the celestial sphere. Imagine Earth's latitude and longitude lines expanding outward and printing themselves onto the celestial sphere. This provides a coordinate grid on the sky that tells the position of any star other than the Sun, just as latitude and longitude tell the position of any point on Earth. In the sky, "latitude" is called **declination** and "longitude" is called **right ascension**.

Declination (dec) is expressed in degrees, arc minutes, and arc seconds, north (+) or south (−) of the **celestial equator** (just as latitudinal positions are described). Capella, the brightest star in the constellation Auriga, has a declination of +46° − 0′ and is, therefore, about halfway between the celestial equator (dec = 0°) and the north celestial pole (dec = +90°).

Right ascension (RA) is expressed not in degrees but in hours (h), minutes (m), and seconds (s) of time, from 0 to 24 hours. Astronomers set up this arrangement long ago because Earth completes one turn in 24 hours, so the celestial sphere appears to take 24 hours to complete one turn around Earth. The zero of right ascension is, by convention, the longitudinal line that runs through the spring equinox. The RA for Capella is 5 hours 17 minutes east of the spring equinox; thinking about RA in angular degree terms results in Capella being about 80 degrees east of the spring equinox. The celestial coordinates of stars remain constant over many years because they are so far away. On the other hand, the Sun, being much closer, moves along the ecliptic throughout the year, travelling through the complete 24-hour RA zones over the calendar year.

2.7 Timekeeping

Even to the casual observer, it is clear that the length of our day is related to Earth's rotational period; the number of days in a month must be associated with the lunar phase period, and the length of a year corresponds to the period of Earth's orbit around the Sun. By now you can see that astronomy is much more precise than vague correspondences.

Timekeeping by Day

Our local meridian is the imaginary line that ends at the north and south celestial poles and cuts through our zenith. The average length of time between successive passes of the Sun across the local meridian is called a **solar day**; this time varies slightly throughout a year, which is why we use the word *average*. Another way of determining

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the length of a day is to measure the time it takes for any star to make successive passes across the local meridian, which we call a **sidereal day** (pronounced sy-deer-ial). A sidereal day is about 23 hours 56 minutes—shorter than a solar day by about 4 minutes. This difference of four minutes is because during a solar day, Earth has travelled along its orbit around the Sun and needs a little more time to rotate before the Sun crosses the meridian. A simple mathematical calculation shows that Earth moves about 1 degree per day around its orbit.

Timekeeping by Month

Timekeeping involving months comes from the lunar phase's cycle, which is about 29.5 solar days, corresponding roughly to the average length of a month, known as a **synodic month**. Synodic comes from the Latin word *synod*, meaning "meeting"—the meeting of the Sun and the Moon at each new moon phase. If, however, we use the stars to measure the length of the lunar cycle, a **sidereal month**, the time turns out to be 27.3 days, which is shorter than a synodic month for the same reason a sidereal day is shorter than a solar day.

Timekeeping by Year

The length of a year is clearly related to the time required for Earth to complete one full orbit around the Sun, about 365.25 days. Again, there are two slightly different time frames. A **sidereal year** is the time taken for a complete orbit relative to the stars, whereas the time between successive spring (or autumnal) equinoxes is called a **tropical year (solar year)**. It should come as no surprise that these two years differ. A sidereal year is longer than a tropical year by about 20 minutes, and the difference is due to the precession of Earth's rotation. If the sidereal year were employed as a calendar, this 20-minute difference would result in seasons slowly shifting throughout the year, although this pattern would take 26 000 years to repeat.

What Time Is It?

After considering various options for timekeeping, what method do you think we actually use? The answer is that we use an aspect of solar time—sort of! The **apparent solar time** is determined by the Sun's position in the sky relative to our local meridian. When the Sun is right on the meridian it is noon; before the Sun gets to the meridian we say that it is *ante meridian* (*ante* meaning "before"), hence a.m. (or am). After noon, when the Sun has passed the meridian, we say that it is *post meridian* (*post* meaning "after"), hence p.m. (or pm). However, each solar day differs from 24 hours by a slight amount because Earth's orbit is not perfectly circular and because of Earth's 23.4-degree tilt. The average solar day is the more important concept and the one used to keep track of time. Using apparent solar time would mean adjusting clocks each day, an unnecessary complication. Clearly, apparent solar time varies with longitude (because of Earth's spin on its axis), and so everybody's apparent solar time is different, unless they happen to be at precisely the same longitude. To alleviate this problem, in the late 1800s, Canadian engineer, Sandford Fleming (Figure 2.14), proposed a system of dividing the Earth into 24 different time zones so that within each time zone the time would be exactly the same. Such a system was universally adopted shortly thereafter.

Calendars

The tropical year (equinox to equinox) is about 365.25 days. If we choose 365 days for one year (the Egyptian concept), the seasons drift through the year by one day in every four years—not a great concept! Julius Caesar introduced the idea that every four years an extra day was to be added to account for this discrepancy: the "leap year." This, the so-called Julian calendar, represented a definite improvement. However, life is rarely this simple. The tropical year is not exactly 365.25 days but rather about 11 minutes short of this value, resulting in the spring equinox moving backwards through the

declination The angular distance of an object on the celestial sphere measured north (+) or south (–) from the celestial equator.

right ascension The angular east-west distance of an object on the celestial sphere measured from the vernal equinox; measured in hours, minutes, and seconds rather than angular degrees.

celestial equator The imaginary line around the sky directly above Earth's equator.

solar day The average time between successive crossings of the Sun on the local meridian (24 hours).

sidereal day The time between successive crossings of any star on the local meridian (23 hours, 56 minutes, 4.09 seconds).

synodic month The time for a complete cycle of lunar phases (about 29.5 days).

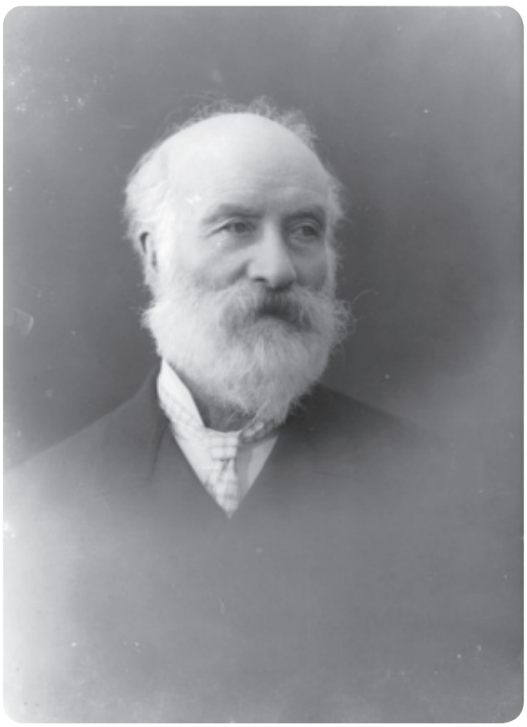
sidereal month The time for the Moon to orbit Earth once relative to any star (about 27.3 days).

sidereal year The time for Earth to complete one full orbit around the Sun relative to any star.

tropical year (solar year) The time between successive spring (or autumnal) equinoxes.

apparent solar time Time measured by the location of the Sun in the local sky such that noon occurs when the Sun crosses the meridian.

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Figure 2.14 Sir Sandford Fleming

calendar by 11 minutes each year, or about 14.5 hours per 80-year lifetime, or about 12 days every 1600 years. So, in 1582, Pope Gregory XIII introduced a slight variation in the calendar, which became known as the Gregorian calendar and is the one we use today. It first set the spring equinox to March 21 and then adjusted the leap year schedule such that each century year would be skipped as a leap year unless it was divisible by 400 (so, the year 2000 would be a leap year, but not 1900, or 2100). This adjustment made the calendar good for thousands of years into the future, and it is now used globally.

2.8 Night Sky Tours

Many students take a university astronomy course to learn about the night sky, hoping to identify various star patterns. In this section, you will find a few "tours" of the night sky visible to Canadian viewers and that cover an entire year of observing. Fortunately, you will not need a telescope—although a decent pair of binoculars may enhance your viewing experience. Instead, you need a location with little or no light pollution, an outdoor easy chair on which to lay to force your eyes upward (a blanket might be required depending on the weather), and your eyes!

This section contains typical star charts, identical to the ones found at the back of your textbook. These charts show the evening sky as viewed from the northern hemisphere at a latitude typical of southern Canada or central Europe. Hold the chart so that the words *southern horizon* are at the bottom, and be sure you are facing south. The night sky will then appear above and behind you as you move up the page. The items indicated on the star chart to the left (eastern horizon) will appear above you and to the left, and so on. If you wish to begin by facing north, turn the star chart upside down and follow the same procedure.

You will notice two arced lines stretching across the chart. The orange one, marked *equator*, is the celestial equator, an imaginary circle around the celestial sphere, and is merely an extension of Earth's equator. The yellow arc marked *ecliptic* is the line described earlier in this chapter that represents the path followed by the Sun across the sky once each year. (The 12 signs of the zodiac, under one of which you were born, are found all along the ecliptic—but that's astrology!)

Now that you have a better understanding of star charts you are ready to take your first "tour" of the night sky, where you will see what the sky looks like over a three- or four-month period. This is possible because the sky does not change much from one night to the next, although over several months the stars visibly shift across the sky as Earth orbits around the Sun.

Our first night sky tour involves the winter sky, where we note some of the more important features of the following constellations: Orion (the Hunter) and his two dogs, Canis Major (the Great Dog), and Canis Minor (the Little Dog), Taurus (the Bull), Gemini (the Twins), and Auriga (the Charioteer) (see Figure 2.15). Orion is one of the most recognized constellations; in Canada, it appears low in the southern sky. Perhaps its most identifiable feature is the belt star formation that appears as a straight line of stars. Actually, these stars are at vastly different distances from us: from left to right they are Alnitak (826 ly), Alnilam (1359 ly), and Mintaka (919 ly). To the upper left is Betelgeuse, the fist star, which is a reddish variable star and 429 ly away; to the lower right is Rigel, the foot star, which is much larger and brighter than our Sun and about 777 ly from us. Just below Orion's belt is M42, a Messier object known as the Orion nebula. This is a collection of stars (some dying and some forming) and dust in our own galaxy—a spectacular telescopic sight, but visible to the naked eye only on a clear night from an area with no light pollution. In the late 1700s a comet hunter, Charles Messier, compiled a list of about 100 non-comet objects,

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Figure 2.15

Northern Hemisphere Sky

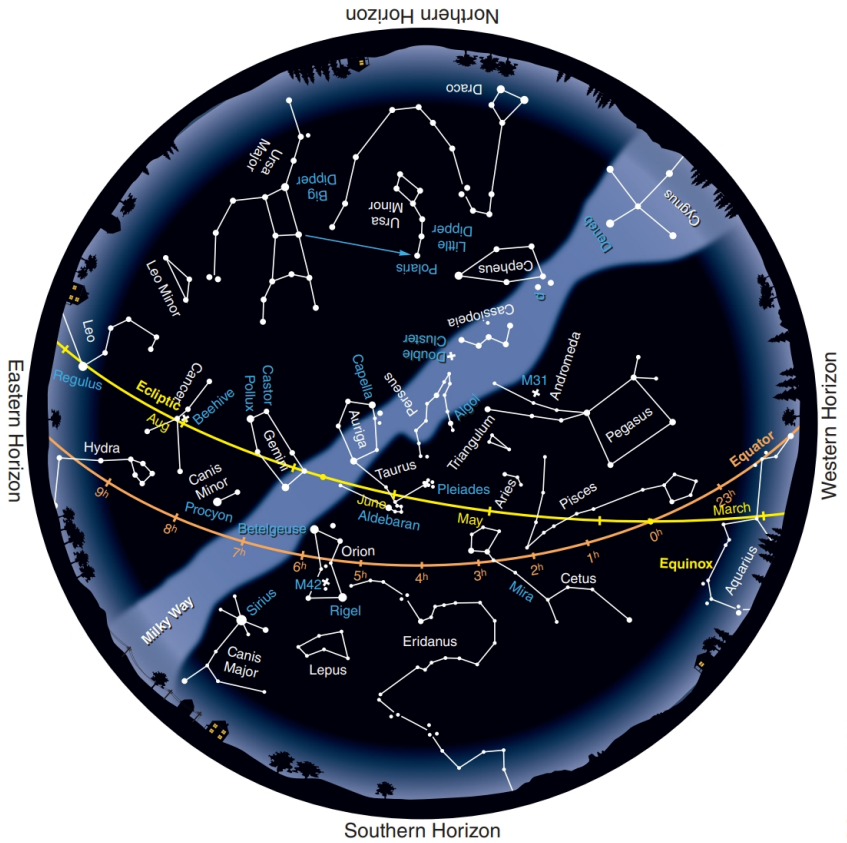
November–December–January

November	midnight
December	10 p.m.
January	8 p.m.

Times are Standard Time; for Daylight Savings Time, add 1 hour.

Months along the ecliptic show the location of the Sun during the year.

Numbers along the celestial equator show right ascension.



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mostly nebulae and star clusters, which became known as Messier objects and were labelled M1, M2, and so on. Today the list includes 110 such objects, and many astronomers endeavour to view the entire list over their lifetime. The belt stars in Orion point downward to Sirius, the Dog Star—the brightest star in the sky and one of the closest at 8.6 ly. Sirius is called the Dog Star because it is the main star in another well-known constellation, Canis Major (the Great Dog). Canis Major is one of two heavenly hounds that follow Orion around the night sky. The other is Canis Minor (the Little Dog), found northeast of the Great Dog. Going in the other direction along Orion's belt, toward the zenith, we arrive at another bright star, Aldebaran, often considered the bull's eye in the constellation Taurus (the Bull). Two star clusters in Taurus are worth noting. The Hyades cluster appears to form the head of Taurus, and the more famous Pleiades (or Seven Sisters) is just northwest of Aldebaran. The horns of Taurus point toward the constellation Gemini (the Twins). The heads of the twins are identified by two equally bright stars, Castor and Pollux: Castor is slightly higher in the sky. To the astute observer, Pollux is somewhat orange in colour, while Castor is clearly white. Finally, we get to Auriga (the Charioteer), above Gemini. The brightest feature of Auriga is the star Capella—a well-known star, often used as a guide by navigators. Near Capella is a triangle of fairly bright stars known as the Kids; Auriga is supposed to have a whip or reins in his right hand (our left) and a family of small goats in his other arm. We could mention many more details about each of these constellations, but that is beyond the scope of this little tour of the Canadian winter sky. There also is a lot of mythology intertwined with the history of these constellations—but that's another university course!

Our second night sky tour takes us through the northern summer sky, where the constellations reviewed include Leo (the Lion), Virgo (the Virgin), Ursa Major (the Great Bear) and Ursa Minor (the Little Bear), and finally Boötes (the Herdsman). Perhaps the most well-recognized northern image is the Big Dipper, which is part of Ursa Major. Interestingly, the Big Dipper by itself is not a constellation, but because it is close to the North Star (Polaris), it is visible throughout Canada all year (see

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Figure 2.16

Northern Hemisphere Sky

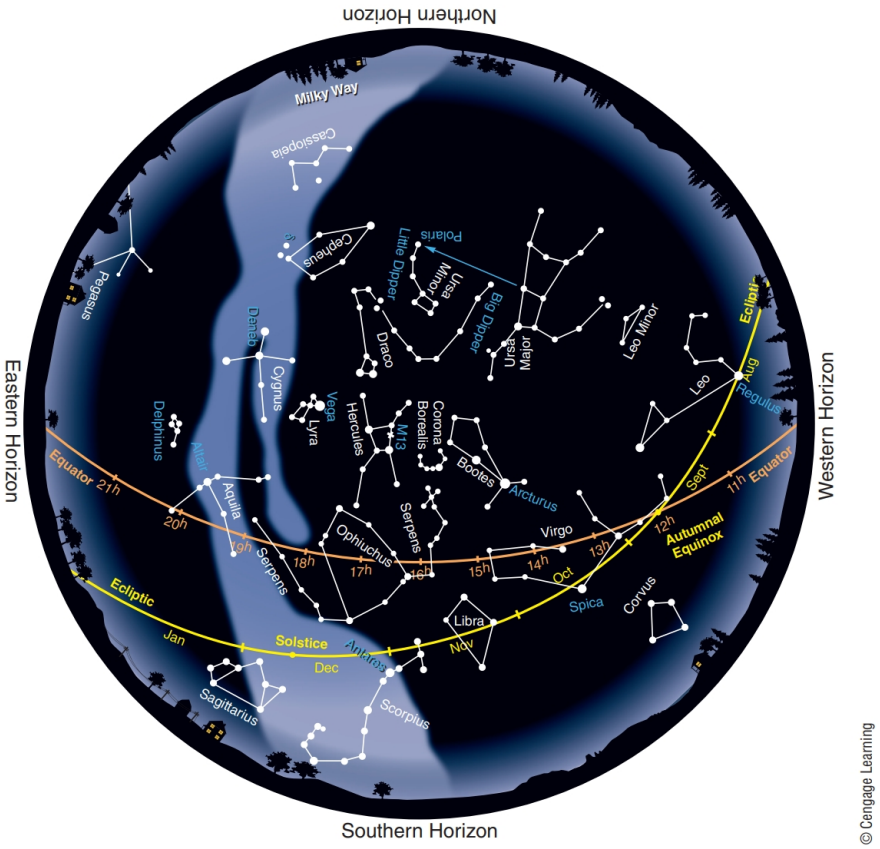
May–June–July

May	midnight
June	10 p.m.
July	8 p.m.

Times are Standard Time; for Daylight Savings Time, add 1 hour.

Months along the ecliptic show the location of the Sun during the year.

Numbers along the celestial equator show right ascension.



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Figure 2.16). Polaris is the brightest star in Ursa Minor, and you can find it by following the line defined by the two outer cup stars of the Big Dipper to the north. Actually, despite its reputation, Polaris is not an overly bright star, being about the 50th brightest star in the entire sky and, for a novice, not all that easy to find. Similarly, Ursa Minor is not always easily visible and requires patience and a current star chart to ensure discovery. Above Ursa Major and slightly to the west is Leo. Leo has several interesting features, not the least of which is a grouping of stars forming its head that is often referred to as the Sickle (because it is shaped like one). Such a named grouping of stars within a constellation is called an *asterism*; the Big Dipper is an asterism. The brightest star in Leo is its foot star, Regulus, which is very close to the ecliptic plane. Farther along the ecliptic plane to the east is Virgo (the Virgin), yet another of the zodiacal constellations, often depicted as a reclining human form. The brightest star in Virgo is Spica, the 15th brightest star, a double star that is 11 times as massive as our Sun. The name Spica has Latin origins meaning "ear of wheat," and is so named because the Sun comes close to Spica in the fall (harvest time); some say the ancients saw Virgo holding a shaft of wheat, the ripe heads represented by this bright star. Higher in the sky (above Virgo) is Arcturus, the 4th brightest star, and the main star in Boötes. Arcturus, quite orange in hue, has already started to die and is fusing helium into carbon in its core (see Chapter 8). Boötes is known as the Herdsman because he is seen to be keeping the celestial animals in order as he "chases" them around the sky. Arcturus, from the Greek for "bear watcher," keeps an eye on Ursa Major, Leo, and Lynx (not discussed here) as he follows them around the pole. Light from Arcturus was used to open the 1933 World's Fair in Chicago; the star was chosen because light had left it at about the same time the fair was previously held in Chicago in 1893.

Our final tour begins along the swath of the Milky Way, which, during the fall and early Canadian winter, cuts across the sky from east to west. On a clear, moonless night away from light pollution, you can see a visibly white ribbon of billions of stars (first observed as such by Galileo more than 400 years ago using his newly constructed telescope) (see Figure 2.17). Peering into this ribbon of stars means you are looking into our

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CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Reg Innell/Toronto Star via Getty Images

Helen Sawyer Hogg

Helen Sawyer Hogg

Helen Sawyer Hogg may have been Canada's most popular astronomer. For more than 30 years, she wrote a hugely popular column for the *Toronto Star*, called "With the Stars." In it, she described major celestial events, included tips for observing the night sky, and discussed important astronomical discoveries. As an undergraduate student in 1925, Helen Sawyer Hogg witnessed a total eclipse of the Sun, which inspired her to become an astronomer. She recalled that "the glory of the spectacle seems to have tied me to astronomy for life, despite my horribly cold feet as we stood almost knee deep in the snow." After graduating, she performed her doctoral studies at Harvard Observatory, but because Harvard did not at the time confer degrees in science to women, she officially obtained her Ph.D. from Radcliffe College in 1931. She then moved to Victoria, British Columbia, where her husband had accepted a position at the Dominion Astrophysical Observatory. She was not offered a position, so acting as her husband's voluntary assistant, Dr. Sawyer Hogg began studying variable stars in globular clusters. She continued her work as a faculty member at the University of Toronto and became a leading world authority on globular clusters. She discovered hundreds of new variable stars and developed new techniques for distance measurements. Catalogues based on her observations are still widely used today. Dr. Sawyer Hogg won numerous awards and honours, and in 1976 she was made a Companion of the Order of Canada. The asteroid Sawyer Hogg is named after her.

Figure 2.17



Northern Hemisphere Sky

August–September–October

August	midnight
September	10 p.m.
October	8 p.m.

Times are Standard Time; for Daylight Savings Time, add 1 hour.

Months along the ecliptic show the location of the Sun during the year.

Numbers along the celestial equator show right ascension.

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galaxy from the vantage point of our solar system, about 28 000 ly from the Milky Way's centre. Our first stop is Cassiopeia (the Queen), almost directly overhead within the Milky Way band and whose brightest five stars form a distinct W. Being fairly close to Polaris, Cassiopeia is visible throughout the year to Canadian observers. Beside Cassiopeia is Cepheus (the King), a much dimmer constellation. Its fourth brightest star, δ Cephei, was determined to be a variable star in the late 1700s and is the star after which all Cepheid variable stars are named. On the other side of Cassiopeia is Andromeda (the Chained Princess), which is home to the famed Andromeda Galaxy (M31), our closest neighbouring galaxy (2.5 million ly away). In mythology Cassiopeia and Cepheus were the parents of Andromeda. The brightest star in Andromeda, Alpheratz, is the corner of the asterism the Great Square of Pegasus. Pegasus (the Winged Horse) is clearly right next to Andromeda; its Great Square makes up the body of the horse and is a great autumn landmark. Rounding out this overhead autumn tour, toward the western horizon but still in the Milky Way ribbon, is Cygnus (the Swan), whose brightest star, Deneb (at the back end of the swan), is one apex of the famous summer asterism the Summer Triangle. The swan's beak is denoted by Albireo, a lovely double star—one distinctly blue and one gold—that is nicely visible in even a small telescope (Figure 2.18).



John Chumack / Science Source / Getty Images

Figure 2.18 Albireo

The **Big Picture**

What Are We? Along for the Ride

We humans are planet walkers. We live on the surface of a whirling planet, and on clear, dark nights we can look outward into space for billions of light-years.

Most of the stars we see are actually not very far away. They are only hundreds, not billions, of light-years from Earth. The vast majority of the stars in the universe are too distant and consequently too faint to see with the unaided eye. For centuries, human cultures have labelled the visible stars with names and divided them into constellations. The constellation Hercules looked down on Plato and Aristotle just as it now looks down on you.

Nearly all of the energy Earth receives comes from the Sun, and as Earth spins on its axis and revolves around its orbit, the changing balance of sunlight produces the changing seasons. Winter and summer seasons have cycled for longer than there have been humans on Earth, and when you watch autumn leaves turn golden, you are part of one of the great astronomical cycles of our planet.

Through it all, the Moon orbits Earth, and cultures through history have made it their timepiece. Your calendar is divided into months, recognizing the cycle of the Moon; your months are divided into four weeks, recognizing the fourfold cycle of the moon's phases.

Busy as you are, take a moment to look up and enjoy the cycles of the sky. They will remind you that you are a planet walker.

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Review and Discussion Questions

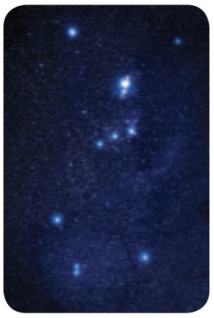
Review Questions

1. What is the difference between an asterism and a constellation? Give some examples.
2. How does the Greek-letter designation of a star give you a clue to its brightness?
3. How did the magnitude system originate in a classification of stars by brightness?
4. What does the word *apparent* mean in "apparent visual magnitude"?
5. In what ways is the celestial sphere a scientific model?
6. If Earth did not rotate, could you define the celestial poles and celestial equator?
7. Where would you go on Earth to place a celestial pole at your zenith?
8. Why does the number of circumpolar constellations depend on the latitude of the observer?
9. If Earth did not rotate, could you still define the ecliptic? Why or why not?
10. Why are the seasons reversed in the southern hemisphere relative to the northern hemisphere?
11. Do the phases of the Moon look the same from every place on Earth, or is the Moon full at different times as seen from different locations?
12. What phase would Earth be in if you were on the Moon when it was full? At first quarter? At waning crescent? Some other phase?
13. Why isn't there an eclipse at every new moon and at every full moon?
14. Why is the Moon red during a total lunar eclipse?
15. **How Do We Know?** What are the main characteristics of a pseudoscience? Can you suggest other examples?

Discussion Questions

1. Most cultures have given names to constellations. Why do you suppose this was a common practice?
2. If you were lost at sea, you could find your approximate latitude by measuring the altitude of Polaris. However, because Polaris isn't exactly at the celestial pole, what else would you need to know to measure your latitude more accurately?
3. Do planets orbiting other stars have ecliptics? Could they have seasons?

Learning to Look



igordabari / Shutterstock.com

1. This photo shows the constellation Orion. Explain why this looks odd to residents of the northern hemisphere.
2. The photo below shows the annular eclipse of May 30, 1984. How is it different from the total eclipse shown in Figure 2.10? Why do you suppose it is different?



© Laurence Marshall

STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *User's Guide to the Sky: Patterns and Cycles*

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
- Interactive Quizzing
- Animations
- Tutorials

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PART ONE

3 The Origin of Modern Astronomy

CHAPTER OUTLINE

3.1 The Birth of Astronomy
3.2 A Revolutionary Idea
3.3 Observing the Patterns of Planetary Motion
3.4 A New Window on the Universe
3.5 The Science of Motion

GUIDEPOST

Have you ever looked up at the sky and marvelled at the multitude of tiny specks of light shining down on you? Have you tried to pick out patterns in the night sky? Have you stared at the full Moon or the sliver of a crescent moon on a dark night? Then you are following in the footsteps of our ancient ancestors who gazed up at the sky thousands of years ago and took the first steps along the long road that has led to our current knowledge of the universe. As you read on, you will learn how the science of astronomy grew out of careful observations and gradual development of the scientific method over thousands of years. You will find that every culture has engaged in and contributed to the development of astronomy, making it a truly global effort. And you will understand that ancient astronomy has shaped not only our scientific thinking but also our culture, art, language, religions, and traditions.

In this chapter you will find answers to three important questions:

- What did early astronomers learn about the motion of stars and Earth's place in the universe?
- What led to our modern understanding of gravity and motion in the universe?
- How did the development of modern astronomy change the way people thought about nature and themselves?

This chapter is not just about the history of astronomy. As astronomers struggled to understand Earth and the universe, they invented a new way of understanding nature—a way of thinking that is now called science.



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If at first the idea is not absurd then there is no hope for it.

Albert Einstein,
physicist and Nobel laureate

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3.1 The Birth of Astronomy

The origins of astronomy arose from the curiosity of our ancestors, who were excellent at observing and recording the world around them and recognizing patterns in what they observed. These skills were critical for their survival, but although they did not know it, careful observation and pattern recognition were also the first steps in what we now call the modern scientific method.

A marvellous example of ancient observations and recordkeeping can be found in Lascaux, France, where Paleolithic cave paintings dating back to 15 000 BCE were discovered in 1940 (Figure 3.1). More than 900 images of animals show incredible attention to detail and anatomical precision. There are also numerous images of geometric figures. Some recent scientific studies indicate that the paintings may have been a star map or astronomical calendar, but there is no conclusive proof that this theory is correct. More convincing evidence of early astronomical observations has been found in Africa, where a carved bone that is 8500 years old shows pictographs of the crescent Moon. Ancient people of central Africa could predict seasons from the orientation of the horns of the crescent Moon each month (again, a result of careful observation and pattern recognition). This allowed them to determine when to plant seeds and grow their crops.



thipjang / Shutterstock.com

Figure 3.1 Paleolithic cave paintings in France from 15 000 BCE may be a star map or represent the zodiac, although this theory has not been conclusively proved.

Archeological sites of ancient cultures of Egypt, British Isles, and Mesoamerica show the results of detailed observation and sophisticated knowledge of the night sky, including the cycles of the Sun, Moon, and planets (see Figure 3.2).

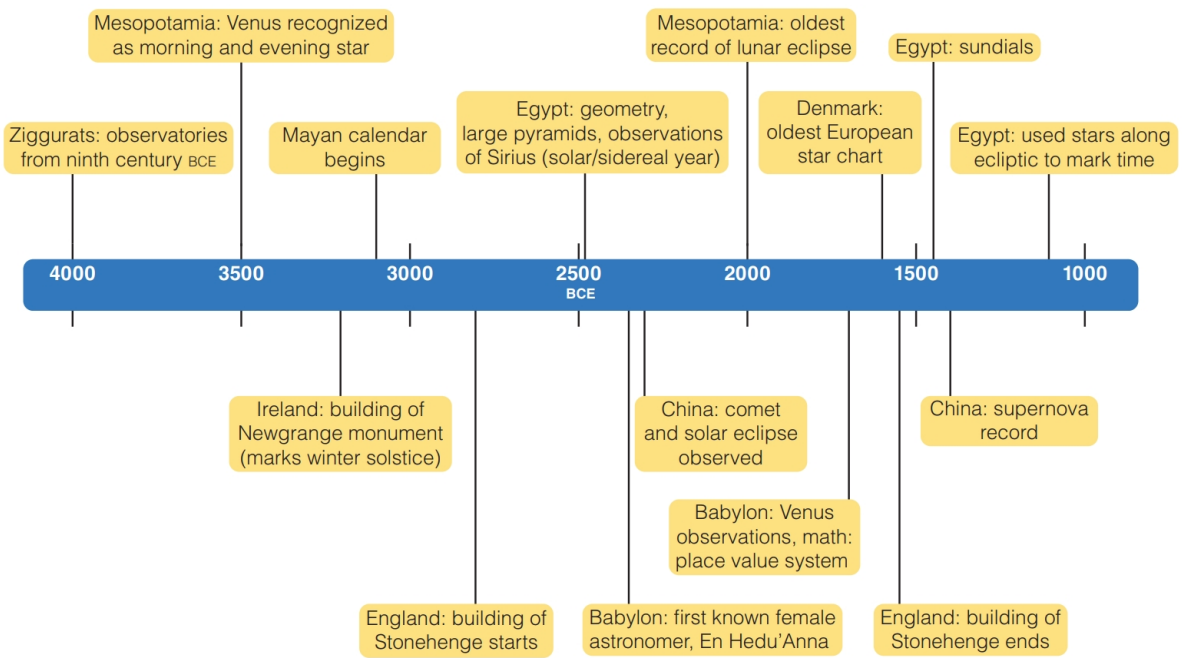


Figure 3.2 Timeline of Astronomy: 4000 BCE to 1000 BCE

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Around 2500 BCE the Egyptians used the first visibility at dawn of the star Sirius to mark the beginning of a 365-day calendar. Sirius, the brightest star in the sky, which they identified with the fertility goddess Isis, first appeared in the predawn sky each year just as the Nile began its life-giving floods. While the rising of the Nile varied year to year, Sirius appeared with perfect regularity. This regular cycle helped them predict planting season and prepare for the floods. The Egyptians were also the first to divide the night and day into 12 hours, but of varying lengths, based on the rising of certain bright stars during summer nights. Our modern 24-hour clock partially owes its origins to the Egyptians.

Other ancient cultures also used astronomical observations for timekeeping. The motions of both the Sun and the Moon played an important role in the marking of time, with the Sun used for predicting seasonal changes and the lunar phases defining monthly changes. A 4000-year-old stone circle in Scotland marks the rise and set of the Moon during a phenomenon called the lunar standstill, which occurs every 18.6 years due to the precession of the Moon's orbital plane. During this time, the most northerly and most southerly rising and setting of the Moon occur every month. It is amazing that the builders of the stone circles in Scotland as well as astronomers in other ancient civilizations appeared to have been aware of this long-term cycle, which required careful observations over many years. At the famous monument at Stonehenge, England, completed around 1550 BCE, giant boulders are roughly aligned with the seasonal motion of the Sun (Figure 3.3). The site may have served as an observatory as well as a sacred ceremonial ground. We cannot be sure of its purpose since there are no written records from that time. The Mayans also built massive ancient structures, such as the Templo Mayor, to mark seasonal events.



mpanch / shutterstock.com

Figure 3.3 Stonehenge. Many ancient monuments such as the one in Stonehenge, England, may have been used to mark solar or lunar events.



New York Public Library / Science Source

Figure 3.4 Early Astronomical Calendar. Dating from about 1000 BCE in Babylon, this early form of astronomical calendar shows the monthly pre-dawn rising of three stars.

Some of the most careful observers and detailed record keepers were the Babylonians. In fact, the first female astronomer recorded in history was named in a Babylonian tablet from 2354 BCE (Figure 3.4). Her name was En Hedu'Anna, and her position was astronomer priestess of the Moon Goddess. Babylonian priests like her in Mesopotamia (modern Iraq) recorded the detailed motions of the visible planets on thousands of tablets more than 4000 years ago. In 763 BCE, a solar eclipse was also observed and recorded by the Babylonians. These ancient astronomers have left their mark on modern astronomy. Today, our constellations of the zodiac are based on patterns identified by the Babylonians.

In 1400 BCE an exciting event was observed and recorded in China—the sudden brightening and dimming of a "guest star." Although they did not know it at the time, the Chinese had made the earliest known record of a supernova explosion. The Chinese also recorded solar and lunar eclipses continuously from the 5th century BCE! In 1054 CE the Chinese recorded another powerful supernova explosion. This spectacular event may have also been depicted in a famous Anasazi rock painting found

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CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY

Inuit Traditions

Living in bare landscape with very few landmarks, Inuit people used stars, the Sun, the Moon, snowdrifts, wind directions, and the behaviour of dogs for finding their way from place to place. Stars were reliable markers for orientation, including Betelgeuse, which the Inuit call Akuttujuuk, and Pleiades, which they call Sakiattiak. Stars were also reliable for predicting the weather: Sirius, or Singuuriq, changes the way it flickers with weather changes, allowing them to make a very precise forecast. Most Inuit societies kept time by the Moon; people used a 13-month lunar calendar whose names reflected natural events occurring in that month.

In the Far North of Canada, where the Sun never rises in deep winter, the Inuit devised ingenious methods based on the rising and setting of stars to mark time. For example, on the winter solstice, the Sun remains below the horizon, but scattered sunlight in the atmosphere is brightest around the star Aagjuk (the Inuit name for Altair). By noting when the Sun's twilight glow is centred on the bright star Altair, the Inuit could tell when the winter solstice occurred. This event was celebrated as it signalled the eventual return of the Sun. The Inuit name for Polaris is Nuuttuittuq, meaning "the one that never moves," a fitting name since Polaris lies almost along Earth's axis and hence does not rotate perceptibly to the naked eye in the night sky, unlike the other stars. The Inuit used Polaris and various bright star constellations to find their way across vast open stretches of snow-covered country, where other geographical markers are difficult to spot. Astronomy was used not only for timekeeping and navigation, but the stars, planets, and celestial phenomena such as the northern lights also played a central role in storytelling and Inuit mythology.



© Corey Hochachka/ Design Pics

Twilight tree silhouettes and stars, with time-lapse photography showing star trails as Earth orbits on its axis. The central star, Polaris/ Nuuttuittuq, lies almost along the axis and does not perceptibly move. Photograph taken in Jasper National Park, Alberta.

on the other side of the world, in New Mexico, USA (Figure 3.5). The supernova explosion was powerful enough to be brighter than Venus and visible during the day for 23 days. In recent times, modern telescopes have been used to capture stunning images of the Crab Nebula, which is the remnant of the supernova explosion of 1054 CE (see Figure 8.10).

The observed connection between the planting seasons and the position of celestial objects led to the development of religions centred on the Sun, the Moon, and other celestial objects personified as deities. Certain ceremonies were designed to please celestial beings, and prayers and rituals were performed to mark important seasonal changes. Many festivals and ceremonies still celebrated in various parts of the world have their roots in ancient practices. Priests were important members of society due to their ability to predict celestial events, which was viewed as a connection to heavenly deities. The association of celestial objects with one or more gods led to the idea that these gods could affect individual human lives. This was the birth of astrology—the search for influences on human lives based on the positions

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HOW DO WE KNOW? 3.1

Wayfinding: Astronomical Navigation

Thousands of years before the invention of modern navigational instruments, those who travelled vast distances, such as over expanses with very few landmarks, across Arctic snow, or across the Pacific Ocean, developed techniques of "wayfinding": that is, observing positions of stars and knowing their particular environment.

Indian and Pacific Ocean sailors created detailed star maps in their minds and elaborate ways of remembering them. The star compass was the basic mental construct for navigation. Hawaiian houses of the stars were places where stars came out of the ocean and went back into the ocean. To find their direction, travellers had to identify the stars and memorize where they rose and set. Constant observation of the sky and monitoring of changes in the Sun's position, ocean swells, types of waves, and bird paths gave information about their position and direction. Polynesians and Micronesians who travelled thousands of kilometres across the open ocean used elaborate stick maps incorporating all the data.



© W. Robert Moore/National Geographic Society/Corbis



George H.H. Huey / Alamy Stock Photo

Figure 3.5 Anasazi rock painting that may be a depiction of the supernova of 1054 CE. The crescent Moon is shown relative to the supernova. The handprint signature may signify that the site is sacred.

of planets and stars in the sky. However, numerous scientific tests have shown that astrological predictions are no more accurate than can be expected from random chance.

As you can see, ancient civilizations were fascinated by the heavens and carefully studied the daily and seasonal motions of celestial objects. The days of the week were named for the Sun, the Moon, and the five planets visible to the naked eye. Astronomical observations benefited and impacted ancient societies in many ways, including timekeeping, efficient agricultural practices, navigation, and the development of religious and ceremonial practices.

To this point, astronomy had involved making observations, recognizing patterns, and making predictions based on the patterns. Another crucial part of the scientific method—building and testing models and hypotheses—was developed next.

The Geocentric Model of the Universe

The ancient Greeks were interested in building models of nature based on reasoning and observation (Figure 3.6). Thales of Miletus, an influential scientist and mathematician,

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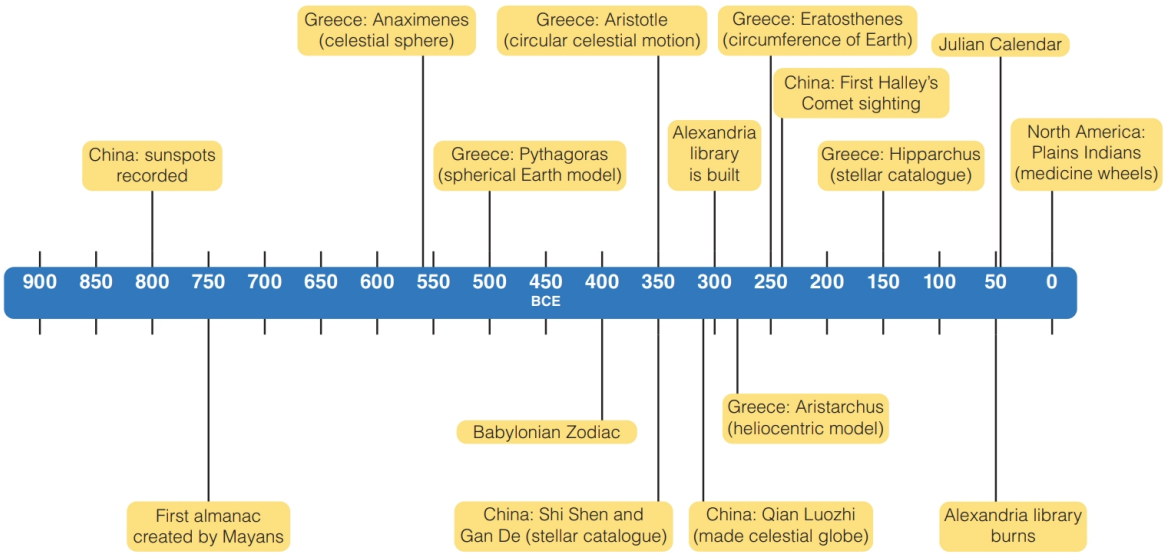
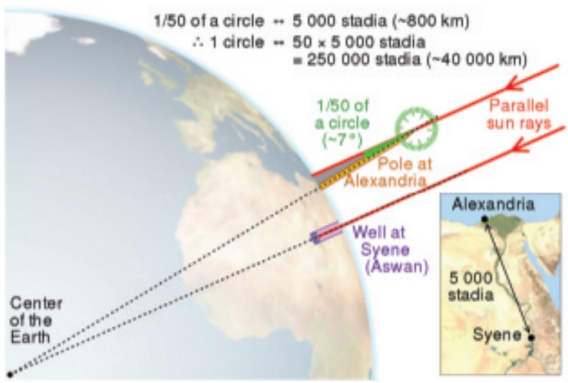


Figure 3.6 Timeline of Astronomy: 900 BCE to 0 CE



cmglee, David Monniaux, jimht at shaw dot ca. This file is licensed under the Creative Commons Attribution-Share Alike 4.0 International license. https://creativecommons.org/licenses/by-sa/4.0/deed.en

Figure 3.7 Eratosthenes's calculation of the circumference of Earth.

assumed that the world was understandable and attempted to create models to explain major events in the universe. It was said that he correctly predicted a solar eclipse, perhaps by using the ancient knowledge of the Babylonians. In 500 BCE, Pythagoras suggested that Earth is a sphere and not flat, as had been previously assumed. His model fit well with observations and the widely held belief that the sphere is an object of geometrical perfection. Based on this spherical model, Eratosthenes was able to calculate Earth's circumference by observing the position of the Sun at noon in two different cities on the first day of summer (Figure 3.7). Incredibly, his estimate was accurate to within a few percent of the currently known value.

first principle Something that seems obviously true and needs no further examination.

The two great authorities of Greek astronomy were the brilliant philosopher Aristotle and Claudius Ptolemy (pronounced TAHL-eh-mee; the initial "P" is silent), a later follower of Aristotle's principles. Study **Visualizing Astronomy 3.1, The Ancient Universe,** and notice three important ideas:

1. Based on their observations, ancient Greek philosophers and astronomers believed that heavenly objects moved on circular paths at constant speed, with Earth motionless at the centre of the universe. This geocentric (Earth at the centre) model was championed by Aristotle. Although a few ancient writers mentioned the possibility that Earth might move, most of them did so in order to point out how that idea is "obviously" wrong.
2. As viewed by you from Earth, the planets seem to follow complicated paths in the sky, including episodes of "backward" (retrograde) motion that are difficult to explain in terms of motion on circular paths at constant speeds.
3. Finally, you can see how Ptolemy created an elaborate geometrical and mathematical model to explain details of the observed motions of the planets, while assuming Earth is motionless at the centre of the universe.

Aristotle lived in Greece from 384 to 322 BCE. He believed as a **first principle** that the heavens were perfect.

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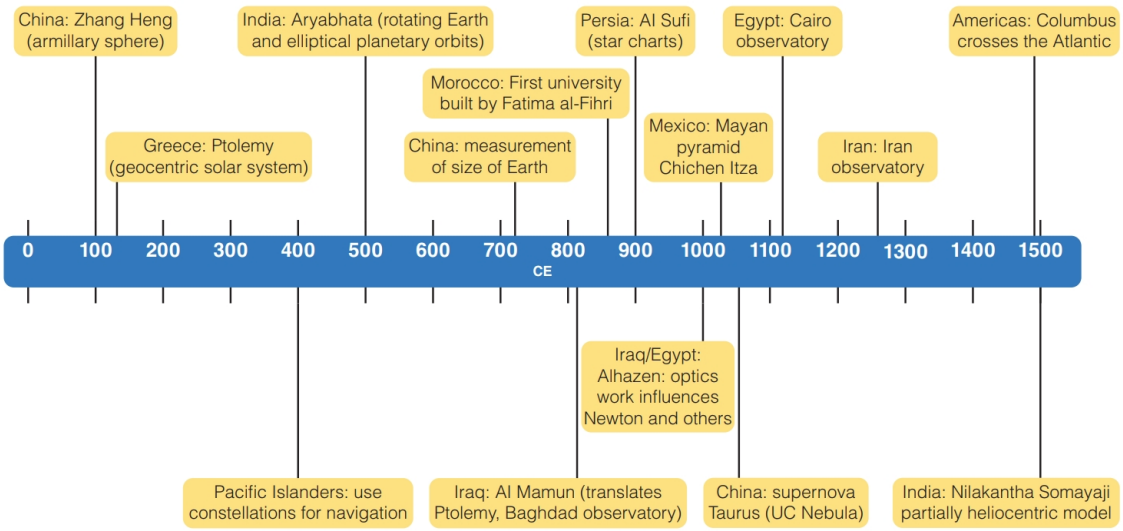


Figure 3.8 Timeline of Astronomy: 0 CE to 1500 CE

Because the sphere and circle were considered the only perfect geometrical figures, Aristotle also believed that all motion in the perfect heavens must be caused by the rotation of spheres carrying objects around in uniform circular motion. Aristotle's writings became so famous that he was known throughout the Middle Ages as "The Philosopher." He set about improving past models to develop an accurate mathematical description of planetary motion.

Claudius Ptolemy, a mathematician who lived roughly 500 years after Aristotle (Figure 3.8), believed in the basic ideas of Aristotle's universe but was interested in practical rather than philosophical questions. For Ptolemy, first principles took second place to accuracy. He set about making an accurate mathematical description of the motions of the planets. Ptolemy weakened the first principles of Aristotle by moving Earth a little off-centre in the model and inventing a way to slightly vary the planets' speeds. His model (published around 140 CE) was a better match to the observed motions and could handle the complicated retrograde motion of the planets. Aristotle's universe, as embodied in the mathematics of Ptolemy's model, dominated ancient astronomy for almost 1500 years.

One of Aristotle's students was none other than the military leader Alexander the Great. Although he used military force to conquer much of the Middle East all the way to India, he also promoted science and encouraged learning. He founded the city of Alexandria in Egypt, renowned for its great library that served as a major centre of knowledge for hundreds of years. One of the most famous library scholars was a woman astronomer and mathematician named Hypatia, who was the director of the observatory in Alexandria. Hypatia, a well-respected scientist and teacher, wrote several books on algebra, geometry, and astronomy. She may have also corrected and extended past work by Ptolemy. She was eventually killed for religious and political reasons, and shortly afterward the library was destroyed. However, Greek knowledge was not lost; it was preserved in the Islamic world. Caliph Al-Ma'mun's House of Wisdom in Baghdad was a great centre of learning around 800 CE. Many ancient texts by scientists and mathematicians from India were also translated into Arabic during this time. Foremost among these was *Aryabhatiya*, by the Indian astronomer and mathematician Aryabhata. This text described a geocentric planetary model, but included the possibility of Earth spinning on its own axis.

Building on ancient texts from Greece, India, China, and Babylon, Arab scientists made many advances in mathematics and astronomy. The Greek geocentric models were expanded and corrected, and many new astronomical observations were made. The names of numerous stars today, such as Algol or Deneb, have their roots in this golden age of astronomy. Although the Ptolemaic geocentric model was widely accepted, some philosophers—such as Abū Rayhān al-Bīrūnī—started thinking about arguments for a heliocentric model (Figure 3.9). It is likely that Arab astronomers were aware of the heliocentric model proposed by the Greek philosopher Aristarchus in 270 BCE. Meanwhile, in India, Nilakantha Somayaji developed a partially heliocentric model that included elliptical orbits

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Visualizing Astronomy 3.1
THE ANCIENT UNIVERSE

1

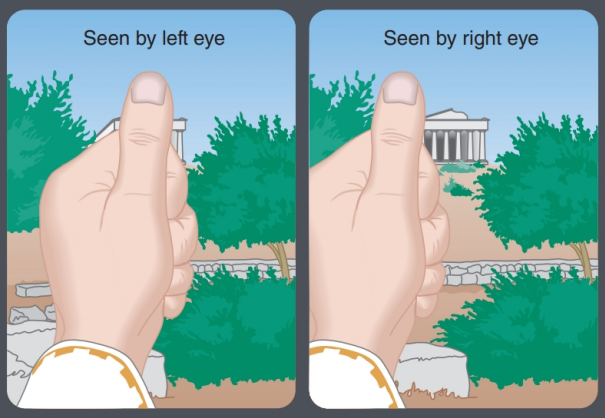
For 2000 years, the minds of astronomers were shackled by a pair of ideas. The Greek philosopher Plato argued that the heavens were perfect. Because the only perfect geometrical shape is a sphere, which carries a point around in a circle as it rotates, and because the only perfect motion is uniform motion, Plato concluded that all motion in the heavens must be made up of combinations of circles turning at uniform rates. This idea was called **uniform circular motion**.

Plato's student Aristotle argued that Earth was imperfect and lay at the centre of the universe. Such a model is known as a **geocentric universe**. His model contained 55 spheres turning at different rates and at different angles to carry the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn across the sky.

Aristotle was known as the greatest philosopher in the ancient world, and for 2000 years his authority chained the minds of astronomers with uniform circular motion and geocentrism. See the model at right.



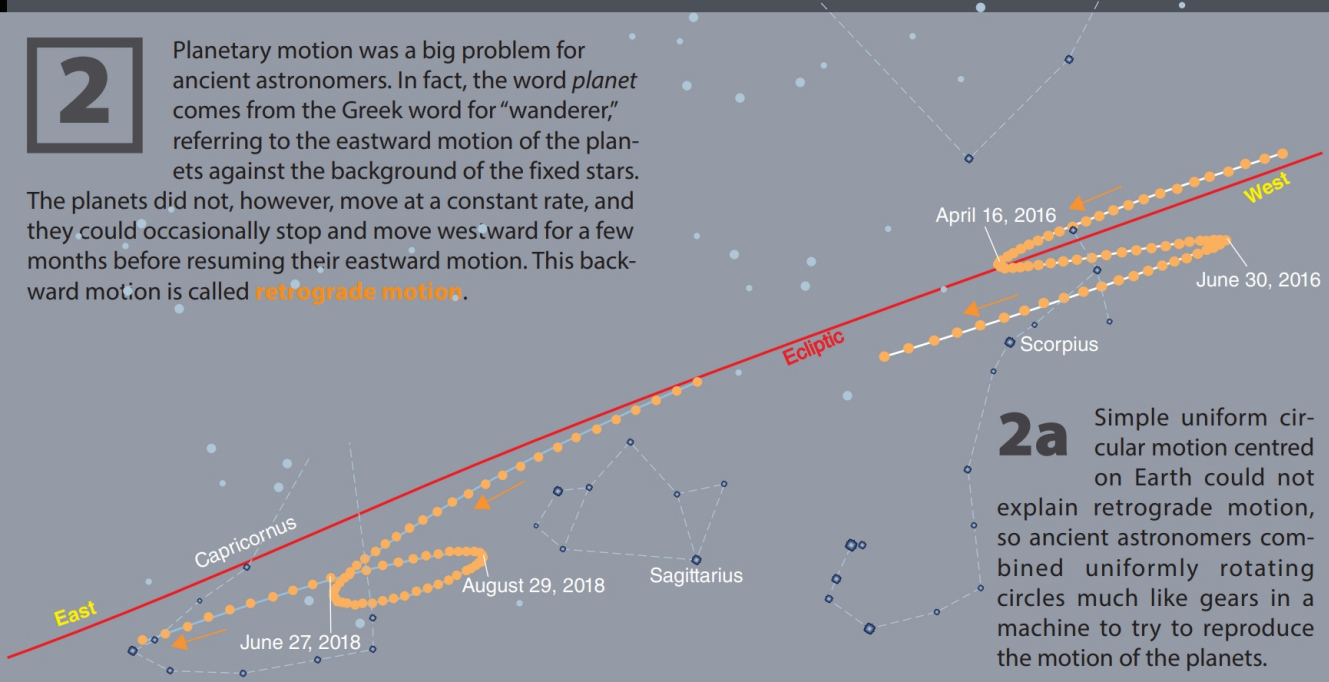
From *Cosmographica* by Peter Apian (1539).



1a Ancient astronomers believed that Earth did not move because they saw no **parallax**, the apparent motion of an object because of the motion of the observer. To demonstrate parallax, close one eye and cover a distant object with your thumb held at arm's length. Switch eyes, and your thumb appears to shift position as shown at left. If Earth moves, ancient astronomers reasoned, you should see the sky from different locations at different times of the year, and you should see parallax distorting the shapes of the constellations. They saw no parallax, so they concluded Earth could not move. Actually, the parallax of the stars is too small to see with the unaided eye.

Every 2.14 years, Mars passes through a retrograde loop. Two successive loops are shown here. Each loop occurs farther east along the ecliptic and has its own shape.

2 Planetary motion was a big problem for ancient astronomers. In fact, the word *planet* comes from the Greek word for "wanderer," referring to the eastward motion of the planets against the background of the fixed stars. The planets did not, however, move at a constant rate, and they could occasionally stop and move westward for a few months before resuming their eastward motion. This backward motion is called **retrograde motion**.



2a Simple uniform circular motion centred on Earth could not explain retrograde motion, so ancient astronomers combined uniformly rotating circles much like gears in a machine to try to reproduce the motion of the planets.

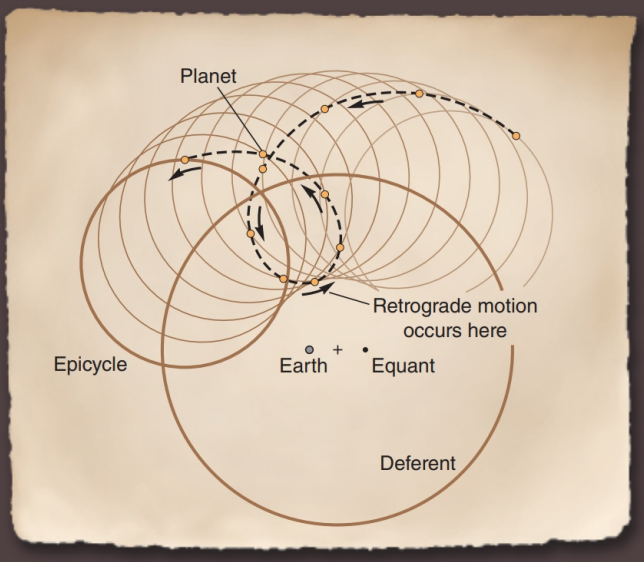
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3 Uniformly rotating circles were key elements of ancient astronomy. Claudius Ptolemy created a mathematical model of the Aristotelian universe in which the planet followed a small circle called the **epicycle** that slid around a larger circle called the **deferent**. By adjusting the size and rate of rotation of the circles, he could approximate the retrograde motion of a planet. See illustration at right.

To adjust the speed of the planet, Ptolemy supposed that Earth was slightly off centre and that the centre of the epicycle moved such that it appeared to move at a constant rate as seen from the point called the **equant**.

To further adjust his model, Ptolemy added small epicycles (not shown here) riding on top of larger epicycles, producing a highly complex model.

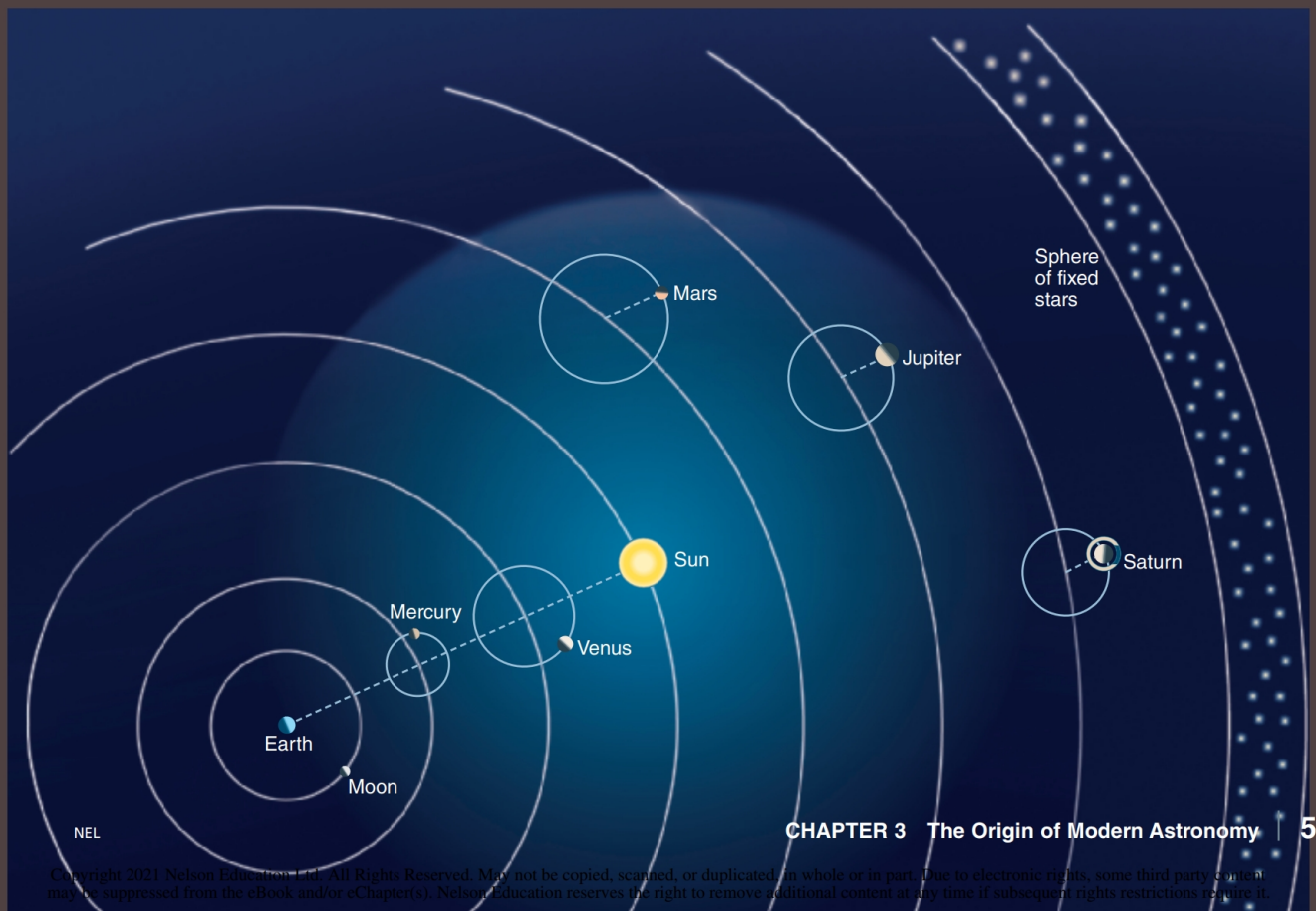


3a Ptolemy's great book *Mathematical Syntaxis* (about the year 140) contained the details of his model. Islamic astronomers preserved and studied the book through the Middle Ages, and they called it *Al Majisti (The Greatest)*. When the book was found and translated from Arabic to Latin in the 12th century, it became known as *Almagest*.

3b The Ptolemaic model of the universe shown below was geocentric and based on uniform circular motion. Note that Mercury and Venus were treated differently from the rest of the planets. The centres of the epicycles of Mercury and Venus had to remain on the Earth–Sun line as the Sun circled Earth through the year.

Equants and smaller epicycles are not shown here. Some versions contained nearly 100 epicycles as generations of astronomers tried to fine-tune the model to better reproduce the motion of the planets.

Notice that this modern illustration shows rings around Saturn and sunlight illuminating the globes of the planets, features that could not be known before the invention of the telescope.



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Figure 3.9 This device is a modern recreation of an ancient Arabic Sun-and-Moon mechanical calendar by Abū Rayhān al-Bīrūnī (10th century CE).

geocentric universe A model of the universe with Earth at the centre, such as the Ptolemaic universe.

heliocentric universe A model of the universe with the Sun at the centre, such as the Copernican universe.

and Earth's rotation. After the fall of Constantinople (Istanbul) in 1453, many scholars travelled to Europe, carrying with them knowledge that contributed to the birth of the Renaissance. The stage was set for a revolution in scientific thought.

3.2 A Revolutionary Idea

Nicolaus Copernicus (originally Mikolaj Kopernik) was born in 1473 in Poland. At the time of his birth—and throughout his life—astronomy in the Western world was based on Ptolemy's geocentric model of Aristotle's universe. In spite of many revisions, the Ptolemaic model was still a poor predictor of planet positions, but because of the authority of Aristotle, it was the officially accepted model. Moreover, because in Aristotle's philosophy the most perfect region was in the heavens and the most imperfect region was at Earth's centre, the classical **geocentric universe** model matched the commonly held Christian view of the geometry of heaven and hell. Anyone who criticized Aristotle's model of the universe was thereby also challenging a belief in the locations of heaven and hell—risking at least criticism and perhaps a serious charge of heresy, with a possible death penalty.

The Heliocentric Model

Copernicus believed that the Sun, not Earth, was the centre of the universe and that Earth rotated on its axis and revolved around the Sun. Copernicus apparently began doubting Ptolemy's geocentric model during his college days. A **heliocentric universe** model (sun-centred, from the Greek word for sun, *helios*) had been discussed before Copernicus's time, but Copernicus was the first person to produce a detailed model with substantial justifying arguments.

Copernicus's book *De Revolutionibus Orbium Coelestium* (*On the Revolutions of Celestial Spheres*) was essentially finished by about 1530. He hesitated to publish, although other astronomers and even church officials concerned about reform of the calendar knew about his work, sought his advice, and looked forward to the book's publication. In 1542 Copernicus finally sent the manuscript for *De Revolutionibus* off to be printed (Figure 3.10). He died in 1543 before the printing was completed.

The most important idea in the book was that the Sun was the centre of the universe. That single innovation had an impressive consequence—the retrograde motion of the planets was immediately explained in a straightforward way without the epicycles that Ptolemy used.

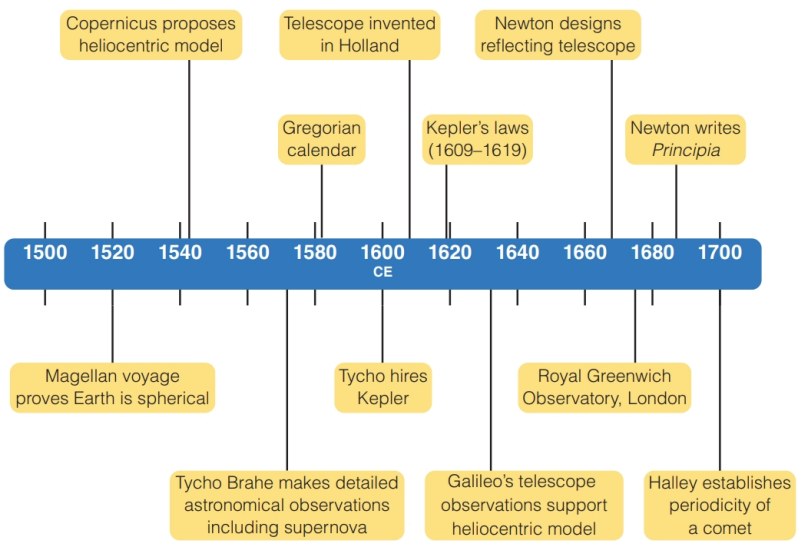
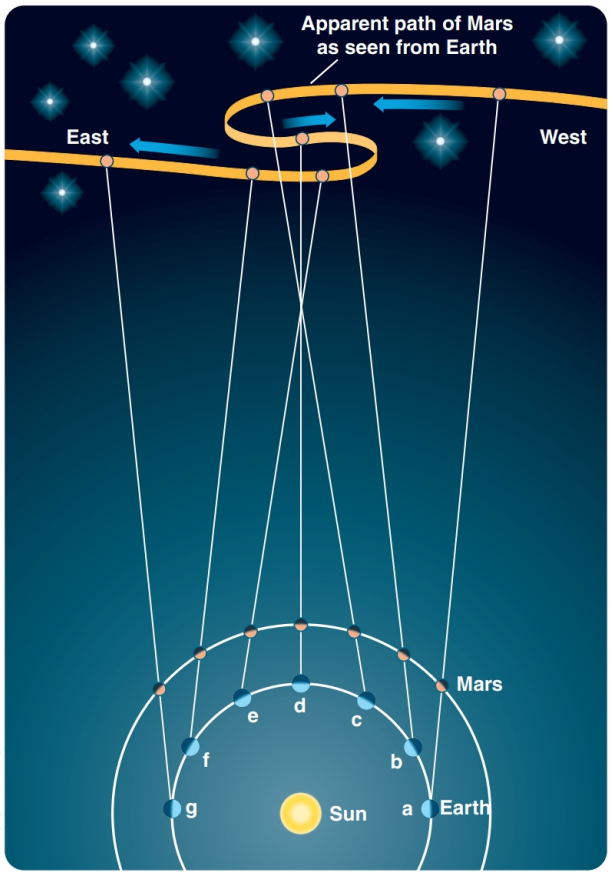


Figure 3.10 Timeline of Astronomy: 1500 CE to 1700 CE

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Figure 3.11 Explanation of apparent retrograde (backward) motion of planets in the heliocentric model. Earth and Mars are shown at equal intervals. Mars appears to slow its eastward motion as Earth overtakes Mars (a–c). As Earth passes Mars (d), Mars appears to move westward. As Earth draws ahead of Mars (e–g), Mars resumes its eastward motion against the background stars.

In the heliocentric model, Earth moves faster along its orbit than the planets that lie farther from the Sun (see Figure 3.11). Consequently, Earth periodically overtakes and passes these planets. Imagine that you are a runner on a track moving along an inside lane. Runners well ahead of you appear to be moving forward relative to background scenery. As you overtake and pass slower runners in outside lanes, they fall behind, seeming to move backward for a few moments relative to the scenery. The same thing happens as Earth passes a planet such as Mars. Although Mars moves steadily along its orbit, as seen from Earth, it seems to slow to a stop and move westward (retrograde) relative to the background stars as Earth passes it (Figure 3.11). Because the planets' orbits do not lie in precisely the same plane, a planet does not resume its eastward motion in precisely the same path it followed earlier. Instead, it describes a loop with a shape that depends on the angle between the two orbital planes.

The heliocentric model was simple and straightforward compared with the multiple off-centre circles of the Ptolemaic geocentric model. However, *De Revolutionibus* failed to immediately disprove the geocentric model for one critical reason: the Copernican model could not predict the positions of the planets any more accurately than the Ptolemaic model could. Copernicus objected to Ptolemy's schemes for moving Earth slightly off-centre and varying the speeds of planet motions. That seemed arbitrary and ugly to Copernicus, so he returned to a strong but incorrect belief in uniform circular motion. Therefore, even though his model put the Sun correctly at the centre of the solar system, it could not accurately predict the positions of the planets as seen from Earth. Copernicus even had to reintroduce small epicycles to match minor variations in the motions of the Sun, Moon, and planets. Astronomers today recognize those variations as due to the planets' real motions in elliptical orbits rather than the incorrect circular orbits that Copernicus had assumed.

You should notice the difference between the Copernican model and the Copernican hypothesis. The Copernican *model* is inaccurate. It includes uniform circular motion and thus does not precisely describe the motions of the planets. But the Copernican *hypothesis* that the solar system is heliocentric is correct—the planets do circle the Sun, not Earth. Note that while this idea is called the Copernican hypothesis, it refers to the heliocentric idea that was proposed by Copernicus as well as other astronomers before him. Although astronomers throughout Europe read and admired *De Revolutionibus* and found Copernicus's astronomical observations and mathematics to have great value, few astronomers believed, at first, that the Sun actually was the centre of the solar system and that Earth moved. How the Copernican hypothesis was gradually recognized as correct has been called the Copernican Revolution, because it was not just the adoption of a new idea but a total change in the way astronomers and the rest of humanity thought about the place of Earth.

The most important consequence of the Copernican hypothesis was not what it said about the Sun but what it said about Earth. By placing the Sun at the centre, the heliocentric model made Earth move along an orbit like the other planets. Making Earth a planet revolutionized humanity's view of its place in the universe (Figure 3.12).

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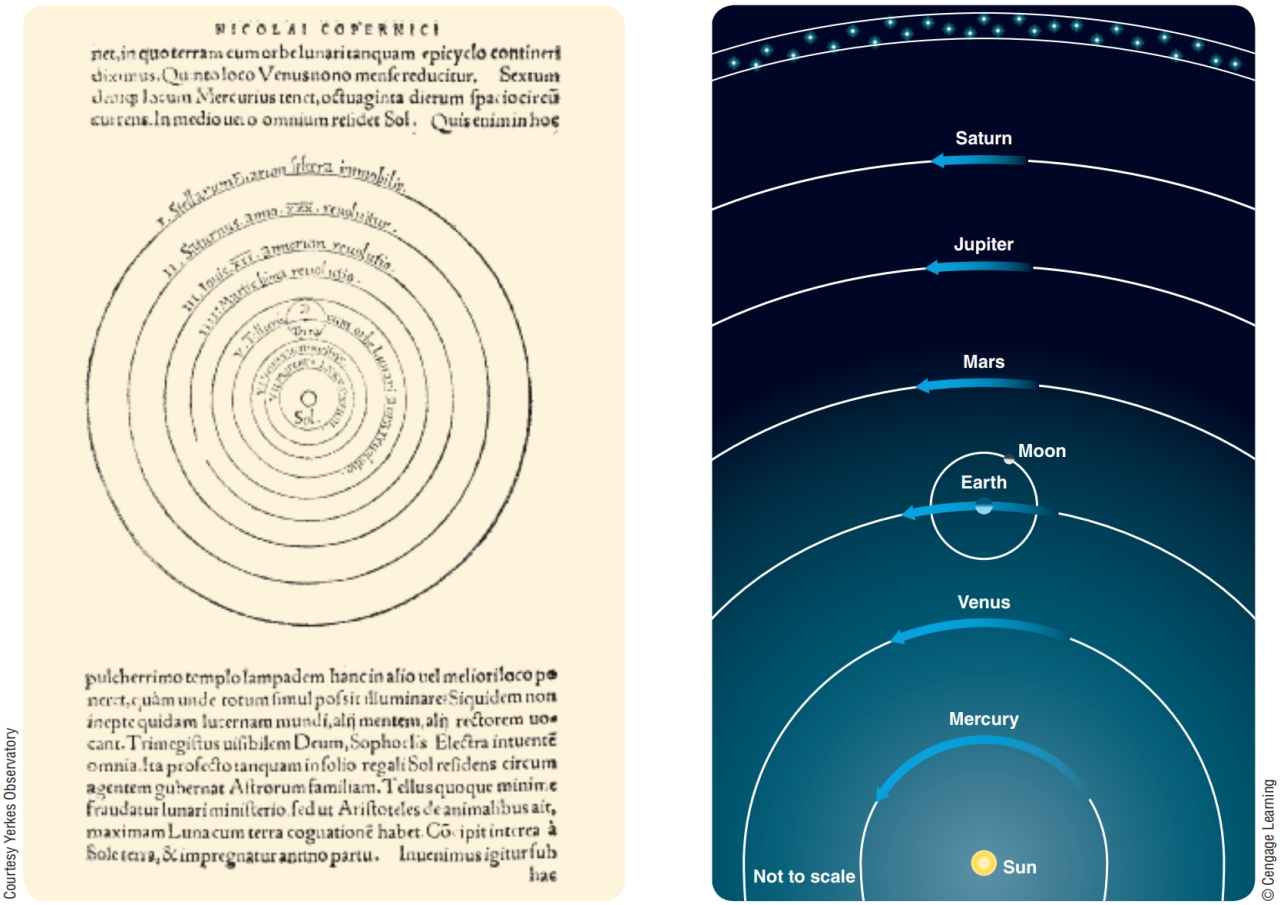


Figure 3.12 The Copernican universe, as reproduced in his book *De Revolutionibus*. (a) Earth and all the known planets revolve in separate circular orbits about the Sun (Sol) at the centre. The outermost sphere carries the immobile stars of the celestial sphere. Notice the orbit of the Moon around Earth (Terra). (b) The model is simple not only in the arrangement of the planets but also in their motions. Orbital velocities (blue arrows) decrease from that of Mercury, the fastest, to that of Saturn, the slowest. Note that Uranus, Neptune, and Pluto were not discovered before the invention of the telescope and are thus not included in this model.

3.3 Observing the Patterns of Planetary Motion

As astronomers struggled to understand the place of Earth, they also faced the problem of planetary motion. How exactly do the planets move? That problem was solved by careful observations and deductions.

The Danish nobleman Tycho Brahe (pronounced Teekoe Bra) is remembered in part for wearing false noses to hide a duelling scar from his college days, but also for building a fabulous observatory. Tycho lived before the invention of the telescope, so his observatory was equipped with wonderful instruments for measuring the positions of the Sun, Moon, and planets using the naked eye and peering along sight lines. For 20 years, Tycho and his assistants measured the positions of the stars and planets.

After the death of the Danish king, Tycho Brahe moved to Prague where he became the Imperial Mathematician to the Holy Roman Emperor Rudolph II. Tycho hired a few assistants including a German school teacher named Johannes Kepler (Figure 3.7). Just before Tycho died in 1601, he asked Rudolph II to make Kepler Imperial Mathematician. The newcomer, Kepler, became Tycho's replacement (though at one-sixth Tycho's salary).

Kepler began by studying the motion of Mars, trying to deduce from the observations how the planet actually moved. By 1606, he had solved the mystery: The orbit of Mars is an ellipse, not a circle. Thus, he abandoned the ancient belief in the circular motion of the planets. But the mystery was even more complex. The planets do not move at uniform speeds along their elliptical orbits. Kepler recognized that they move faster when close to the

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HOW DO WE KNOW? 3.2



Creating New Ways to See Nature: Scientific Revolutions

The Copernican Revolution is often cited as the perfect example of a scientific revolution. Over a few decades, astronomers abandoned a way of thinking about the universe that was almost 2000 years old and adopted a new **paradigm** (pronounced para-dyme), or set of scientific ideas and assumptions. The pre-Copernicus geocentric paradigm survived for many centuries, until a new generation of astronomers overthrew the old paradigm and established a new, heliocentric paradigm.

A scientific paradigm is powerful because it shapes perceptions by determining which questions are important and what evidence is significant. Therefore, it is often difficult to recognize how paradigms limit what you can understand. Though the geocentric paradigm contained problems that seem obvious to a modern mind, ancient astronomers lived and worked inside that paradigm and had difficulty seeing those problems. Overthrowing an existing paradigm is not easy because you must learn to see nature in an entirely new way.

You can find examples of scientific revolutions in many fields. They have been difficult and controversial because they have involved the overthrow of accepted paradigms, but that is why scientific revolutions are exciting. They give you an entirely new insight into how nature works—a new way of seeing the world.

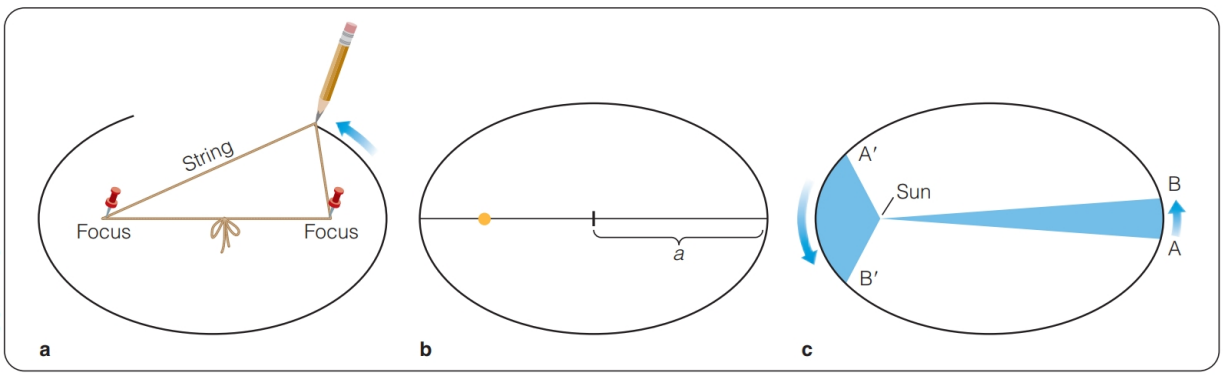
Sun and slower when farther away, and so he abandoned both uniform motion and circular motion and thereby finally solved the problem of planetary motion. Later he discovered that the period of each planet's orbit is related to that orbit's radius. Kepler published his results in 1609 and 1619 in books called, respectively, *Astronomia Nova* (*New Astronomy*) and *Harmonice Mundi* (*The Harmony of the World*).

Kepler's Three Laws of Planetary Motion

Although Kepler dabbled in the philosophical arguments of the day, he was a mathematician, and his triumph was the solution of the problem of the motion of the planets. The key to his solution was the **ellipse**. An ellipse is a figure drawn around two points, called *foci*, in such a way that the distance from one focus to any point on the ellipse and back to the other focus equals a constant. This makes it easy to draw ellipses with two thumbtacks and a loop of string. Press the thumbtacks into a board, hook the string about the tacks, and place a pencil in the loop. As you can see in Figure 3.13a, if you keep the string taut as you move the pencil, you can trace out an ellipse.

paradigm A commonly accepted set of scientific ideas and assumptions.

ellipse A closed curve around two points, called foci, such that the total distance from one focus to the curve and back to the other focus remains constant.



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Figure 3.13 The geometry of elliptical orbits. (a) Drawing an ellipse with two tacks and a loop of string. (b) The semi-major axis, *a*, is half of the longest diameter. (c) Kepler's second law is demonstrated by a planet that moves from *A* to *B* in one month and from *A′* to *B′* in the same amount of time. The two blue segments have the same area. Hence the planet is travelling faster in its orbit from *A′* to *B′* than from *A* to *B*.

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semi-major axis (*a*) Half of the longest diameter of an ellipse.

eccentricity (e) A number between 1 and 0 that describes the shape of an ellipse (how elongated it is); the distance from one focus to the centre of the ellipse divided by the semi-major axis.

The geometry of an ellipse is described by two simple numbers. The **semi-major axis, *a***, is half of the longest diameter (Figure 3.13b). The **eccentricity, *e***, of an ellipse is half the distance between the foci divided by the semi-major axis. The eccentricity of an ellipse tells you about its shape: If *e* is nearly equal to one, the ellipse is very elongated; if *e* is close to zero, the ellipse is more circular. To draw a circle with the string and tacks shown in Figure 3.13a, you would move the two thumbtacks together, which shows that a circle is the same as an ellipse with eccentricity equal to zero. As you move the thumbtacks farther apart, the ellipse becomes flatter and the value of its eccentricity moves closer to 1.

Kepler used ellipses to describe the motion of the planets in three fundamental rules that have been tested and confirmed so many times that astronomers now refer to them as "natural laws." They are commonly called Kepler's laws of planetary motion; these are summarized in Table 3.1.

Kepler's first law states that the orbits of the planets around the Sun are ellipses with the Sun at one focus. Thanks to the precision of Tycho's observations and the sophistication of Kepler's mathematics, Kepler was able to recognize the elliptical shape of the orbits even though they are nearly circular. Of the planets known to Kepler, Mercury has the most elliptical orbit, which you can measure in Figure 3.14, but even it deviates only slightly from a circle.

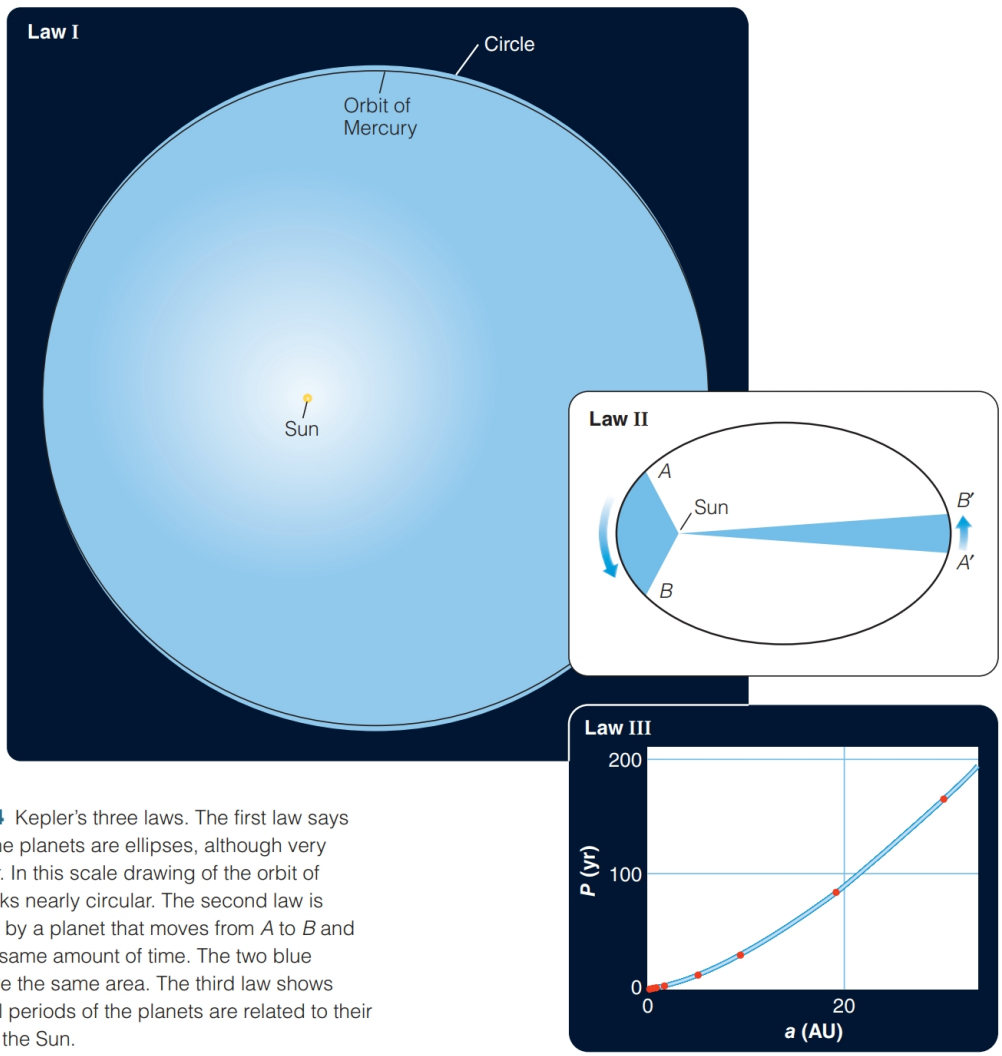


Figure 3.14 Kepler's three laws. The first law says the orbits of the planets are ellipses, although very nearly circular. In this scale drawing of the orbit of Mercury, it looks nearly circular. The second law is demonstrated by a planet that moves from *A* to *B* and *A*' to *B*' in the same amount of time. The two blue segments have the same area. The third law shows that the orbital periods of the planets are related to their distance from the Sun.

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Table 3.1 | Kepler's Laws of Planetary Motion

I.	The orbits of the planets are ellipses with the Sun at one focus.
II.	A line from a planet to the Sun sweeps over equal areas in equal intervals of time.
III.	A planet's orbital period (expressed in years) squared is proportional to its average distance from the Sun (expressed in AU) cubed: $P_y^2 = a_{AU}^3$

Kepler's second law states that a line from the planet to the Sun sweeps over equal areas in equal intervals of time. This means that when the planet is closer to the Sun and the line connecting it to the Sun is shorter, the planet moves more rapidly to sweep over the same area that is swept over when the planet is farther from the Sun. For example, in Figure 3.14 the planet would move from point A to point B in one month, sweeping over the area shown. But when the planet is farther from the Sun, one month's motion would be shorter, from A' to B'. The time that a planet takes to travel around the Sun once is its orbital period, P, and its average distance from the Sun equals the semi-major axis of its orbit, a. Kepler's third law tells us that these two quantities, orbital period and semi-major axis, are related: Orbital period squared is proportional to the semi-major axis cubed. For example, Jupiter's average distance from the Sun (which equals the semi-major axis of its orbit) is 5.2 AU. The semi-major axis cubed would be about 140.6, so the period must be the square root of 140.6, roughly 11.8 years.

It is important to note that Kepler's three laws are **empirical**. That is, they describe a phenomenon based only on observations and without explaining why it occurs. Kepler derived them from Tycho's extensive observations without referring to any first principles, fundamental assumptions, or theory. In fact, Kepler never knew what held the planets in their orbits or why they continued to move around the Sun in the ways he discovered.

3.4 A New Window on the Universe

Galileo Galilei was born in the Italian city of Pisa in 1564 and studied medicine at the university there. His true love, however, was mathematics, and he eventually became professor of mathematics at the university at Padua, where he remained for 18 years. During this time, Galileo seemed to have adopted the Copernican model, although he admitted in a 1597 letter to Kepler that he did not support that model publicly, fearing criticism.

Telescopic Observations

It was the telescope that drove Galileo to publicly defend the heliocentric model. Galileo did not invent the telescope. It was probably invented around 1608 by lens makers in Holland. Galileo, hearing descriptions in the fall of 1609, was able to build working telescopes in his workshop (Figure 3.15). Galileo was also not the first person to look at the sky through a telescope, but he was the first person to observe the sky carefully and

empirical Description of a phenomenon based only on observations and without explaining why it occurs.



GIANNI TORTOLI / SCIENCE PHOTO LIBRARY

Figure 3.15 Galileo's telescope that he used to observe the moons of Jupiter.

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HOW DO WE KNOW? 3.3



Hypothesis, Theory, and Law: Levels of Confidence

Even scientists misuse the words *hypothesis*, *theory*, and *law*. You must try to distinguish these terms from one another because they are key elements in science.

A **hypothesis** is a single assertion or conjecture that can be tested. It could be true or false. "All Canadians love maple syrup" is a hypothesis. To know whether it is true or false, you need to test it against reality by making observations or performing experiments. Copernicus asserted that the universe was heliocentric; his assertion was a hypothesis subject to testing.

In Scientific Models—in Chapter 2, **How Do We Know? 2.1**—you saw that a model is a description of some natural phenomenon; it can't be right or wrong. A model is not a conjecture of truth but merely a convenient way to think about a natural phenomenon. Consequently, a model such as the celestial sphere is not a hypothesis. Copernicus used his hypothesis to build a model, but they are not the same thing.

A **theory** is a system of rules and principles that can be applied to a wide variety of circumstances. A theory may have begun as one or more hypotheses, but it has been tested, expanded, and generalized. Many textbooks refer to the "Copernican theory," but some historians argue that it was not complete and had not been tested enough to be a theory. It is probably better to call it the Copernican hypothesis. Note that people use "theory" and "opinion" or "idea" interchangeably in everyday language. Hence when someone says that something is "just a theory" they mean it is "just an opinion" or "just an idea." In science a theory is most certainly not just an opinion or an idea. A scientific theory such as the theory of relativity undergoes rigorous testing and verification before it is widely accepted.

A **natural law** is a theory that has been refined, tested, and confirmed so often that scientists have great confidence in it. Laws are the most fundamental principles of scientific knowledge. Kepler's laws are good examples.

Confidence is the key to understanding these terms. Scientists have more confidence in a theory than in a hypothesis and great confidence in a natural law. Nevertheless, scientists are not always consistent about these words. For example, Einstein's theory of relativity is much more accurate than Newton's laws of gravity and motion, but traditionally, scientists refer to "Einstein's theories" and "Newton's laws." Darwin's theory of evolution has been tested many times, and scientists have great confidence in it, but no one refers to Darwin's law. These distinctions are subtle and sometimes depend more on custom than on levels of confidence.



Franklin & Marshall College/Grundy Observatory/Mike Seeds

hypothesis A conjecture, subject to further tests, that accounts for a set of observations.

theory A system of assumptions and principles applicable to a wide range of phenomena that has been repeatedly verified.

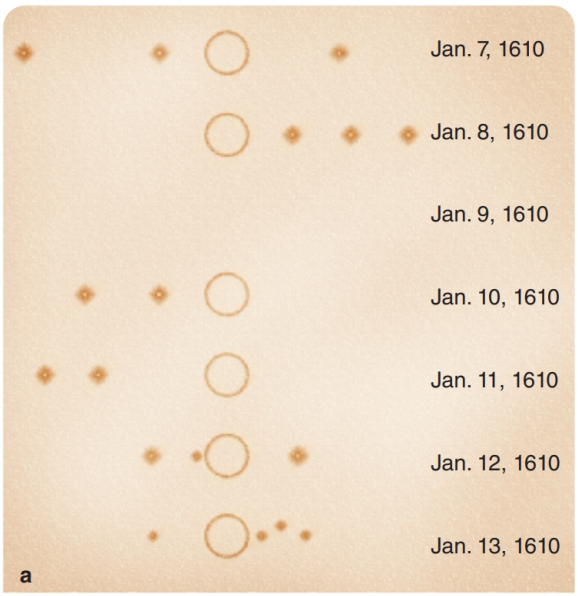
natural law A theory that has been so well confirmed that it is almost universally accepted as correct.

apply his observations to the main theoretical problem of the day—the place of Earth.

What Galileo saw through his telescopes was so amazing he rushed a small book into print, *Sidereus Nuncius* (*The Starry Messenger*). In that book he reported two major discoveries about the solar system. First, the Moon was not perfect. It had mountains and valleys on its surface, and Galileo used the shadows to calculate the height of the mountains. Aristotle's philosophy held that the Moon was perfect, but Galileo showed that it was not only imperfect but was even a world like Earth. Second, Galileo's telescope revealed four new "planets" circling Jupiter—planets that we know today as the Galilean moons of Jupiter, as shown in Figure 3.16.

The moons of Jupiter supported the heliocentric model over the geocentric model. Critics of the sun-centred model had said Earth could not move because the Moon would be left behind; but Jupiter moved and did not leave its satellites behind. Galileo's discovery suggested that Earth, too, could move without losing

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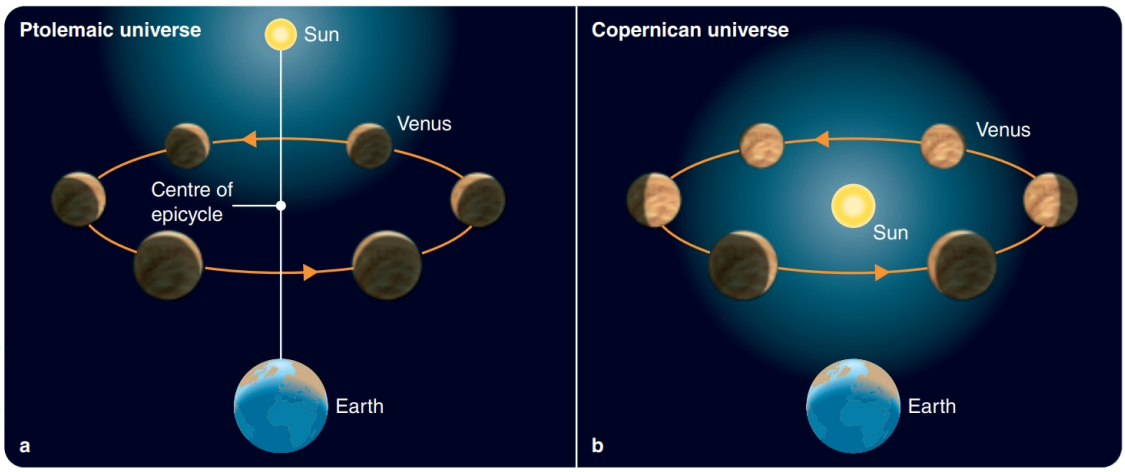
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Figure 3.16 (a) On the night of January 7, 1610, Galileo saw three small "stars" near the bright disk of Jupiter and sketched them in his notebook. On subsequent nights (except January 9, which was cloudy), he saw that the stars were actually four moons orbiting Jupiter. (b) This photograph, taken through a modern telescope, shows the overexposed disk of Jupiter and three of the four Galilean moons.

its moon. Also, Aristotle's philosophy included the belief that all heavenly motion was centred on Earth. Galileo showed that Jupiter's moons revolve around Jupiter, so there could be centres of motion other than Earth. Later, after the *Messenger* was published, Galileo noticed that Jupiter's innermost moon had the shortest orbital period and the moons farther from Jupiter had proportionally longer periods. In this way, Jupiter's moons made up a harmonious system ruled by Jupiter, just as the planets in the heliocentric universe were a harmonious system ruled by the Sun. This similarity didn't constitute proof, but Galileo saw it as an indication that the solar system could be sun-centred and not Earth-centred.

In the years of further exploration with his telescope, Galileo made additional fundamental discoveries. When he observed Venus, Galileo saw that it was going through phases like those of the Moon. In the Ptolemaic model, Venus moves around an epicycle centred on a line between Earth and the Sun. If that were true, it would always be seen as a crescent, like the model in Figure 3.17a. But Galileo saw Venus go through a complete set of phases, including full and gibbous, which proved that it did indeed revolve around the Sun (Figure 3.17b).

Sidereus Nuncius was popular and made Galileo famous. In 1611, Galileo visited Rome and was treated with great respect. He had friendly discussions with the powerful Cardinal Barberini, but because he was outspoken, forceful, and sometimes tactless he offended other important people who questioned his telescopic discoveries. Some critics said he was wrong, and others



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Figure 3.17 (a) If Venus moved in an epicycle centred on the Earth–Sun line, as required by the geocentric model, it would always appear as a crescent. (b) Galileo's telescope showed that Venus goes through a full set of phases, proving that it must orbit the Sun. Note that the Sun, Venus, and Earth lie in the same plane.

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speed The rate at which an object moves (changes position); the total distance moved divided by the total time taken to move that distance.

velocity Both the speed and direction of travel of an object.

said he was lying. Some refused to look through a telescope lest it mislead them, and others looked and claimed to see nothing (hardly surprising given the awkwardness of those first telescopes). When Galileo visited Rome again in 1616, Cardinal Bellarmine interviewed him privately and ordered him to cease public debate about models of the universe, an order Galileo appears to have mostly followed.

The Inquisition banned books relevant to the Copernican hypothesis, although *De Revolutionibus* itself was only suspended pending revision because it was recognized as useful for its predictions of planet positions. Everyone who owned a copy of the book was required to cross out certain statements and add handwritten corrections stating that Earth's motion and the central location of the Sun were only theories and not facts.

In 1623, Galileo's friend Cardinal Barberini became pope, taking the name Urban VIII. Galileo went to Rome in an attempt to have the 1616 order to cease debate lifted. Although that attempt was unsuccessful, Galileo began to write a massive defence of the heliocentric model that was printed in 1632.

Called *Dialogo Sopra i Due Massimi Sistemi del Mondo* (*Dialogue Concerning the Two Chief World Systems*), it confronts the ancient astronomy of Aristotle and Ptolemy with the sun-centred model. Galileo wrote the book as a debate among three friends. Salviati is a swift-tongued defender of Copernicus; Sagredo is intelligent but largely uninformed; Simplicio is a dim-witted defender of Ptolemy. The book was a clear defence of Copernicus, and, either intentionally or unintentionally, Galileo exposed the pope's authority to ridicule. Galileo was interrogated by the Inquisition and possibly threatened with torture. The Inquisition condemned Galileo not primarily for heresy but for disobeying the orders given him in 1616. In 1633, at the age of 70, kneeling before the Inquisition, Galileo read a recantation admitting his errors. Legend has it that as he rose he whispered, *"E pur si muove"* ("Still it moves"), referring to Earth. Although he was sentenced to life imprisonment, he was actually confined at his villa for the next 10 years, perhaps through the intervention of the pope. He died there in 1642, 99 years after the death of Copernicus. Three hundred and fifty years later, in 1992, Pope John Paul II made a formal statement acknowledging the unjust condemnation of Galileo by the Roman Catholic Church.

3.5 The Science of Motion

The problem of the place of Earth was resolved by the Copernican Revolution, but the problem of planetary motion was only partly solved by Kepler's laws. It was not known why the planets obeyed Kepler's laws. And how could Earth move without leaving the Moon behind? For the last 10 years of his life, Galileo studied the nature of motion, especially the accelerated motion of falling bodies. Although he made some important progress, he was not able to relate his discoveries about motion to the heavens. That final step was taken by Isaac Newton.

Galileo died in January 1642. Almost a year later, Isaac Newton was born in the English village of Woolsthorpe (Figure 3.18). Newton was a quiet child from a farming family, but his work at school was so impressive that his uncle financed his education at Trinity College Cambridge, where he studied mathematics and physics. In 1665, plague swept through England, and the colleges were closed. During 1665 and 1666, Newton spent his time back home in Woolsthorpe, thinking and studying. It was during these years that he made most of his scientific discoveries. Among other things, he studied optics, developed three laws of motion, probed the nature of gravity, and invented calculus. The publication of his work in his book *Principia* in 1687 placed the fields of physics and astronomy on a new firm base.

It is beyond the scope of this book to analyze all of Newton's work, but his laws of motion and gravity had a huge impact on the future of astronomy. To understand his work, we must begin with a general framework for describing the motion of any object. Position and time specify where and when an object is. **Speed** is the rate at which an object moves (changes position). It is the total distance moved divided by the total time taken to move that distance. For example, if it took you two hours to travel 100 km, your speed was 50 km/h. Although we are used to thinking of speeds in km/h, in science the Standard International (SI) units are metres/second. **Velocity** specifies both speed and direction of travel of an object. For example, if car A moves 60 km east in 2 hours and car B moves 60 km south in 2 hours, they have the same speed of 30 km/h, but their velocities are different because they are travelling in different directions. Velocity changes if (a) the speed changes, (b) the direction changes, or (c) both speed and direction change.

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Figure 3.18 This apple tree at Trinity College, Cambridge, commemorates the famous story of the apple that fell on Newton and led him to the theory of gravity, although it is not known if the story is true.

Acceleration is the rate of change of velocity with time: the change in velocity divided by the time taken for the change to occur. Since velocity changes if speed changes, speeding up is an example of acceleration, and slowing down is negative acceleration (in a direction opposing the direction of travel); that is, deceleration. On the other hand, velocity also changes if there is a change of direction, so turning is also an example of acceleration.

Newton realized that the motion of all objects is a result of the forces (pulls or pushes) acting on them. He was able to find three universal laws of motion that made it possible to predict exactly how a body would move if the forces acting on it were known (see Table 3.2). Newton's first law of motion states that an object remains at rest or at constant velocity unless a net force acts to change its speed or direction. For example, when your car is at rest or travelling at a constant speed and direction, the forces exerted by the wheels to drive you forward are balanced by the wind resistance and other forces in such a way that the net (total) force is zero. If you wanted to speed up or slow down or change direction, additional force must be applied by pushing on the accelerator or the brake, or by turning the wheel. The effect of this additional force is described by Newton's second law. If the mass (amount of matter) of the object does not change, the acceleration is proportional to the force exerted. Hence, if you want to double your acceleration the applied force must be doubled.

acceleration The rate of change of velocity with time.

An example of acceleration that we are all familiar with is the acceleration due to gravity. All falling objects on Earth have a constant acceleration downward toward the centre of Earth. This acceleration was first pointed out by Galileo. The acceleration due to gravity, g, is 9.8 metres per second per second, more commonly written as 9.8 m/s^2. This means that if you drop any object, say an apple, from rest, its speed will increase by roughly 10 m/s with each second of falling, if one ignores air resistance. After the first second its speed will be roughly 10 m/s; after two seconds its speed will be 20 m/s, and so on until it crashes into the ground. Conversely, if you throw the apple into the air, there is still a constant acceleration of 9.8 m/s^2 downward. Hence, the speed of the apple will *decrease* by roughly 10 m/s every second until it comes to a standstill, at which point it will start falling back toward the ground with its speed increasing by 10 m/s every second.

The Universal Theory of Gravitation

When Newton thought carefully about motion, he realized that some force must pull the Moon toward Earth's centre. If there were no such force altering the Moon's motion, it would continue moving in a straight line and leave Earth forever. It can circle Earth only if Earth pulls on it. Newton's insight was to recognize that the force that holds the Moon in its orbit is the same force of gravity that makes apples and all other objects fall to the ground on Earth.

Table 3.2 | Newton's Three Laws of Motion

I.	An object continues at rest or in uniform motion in a straight line unless acted upon by some force.
II.	An object's change of motion is proportional to the force acting on it, and is in the direction of the force.
III.	When one body exerts a force on a second body, the second body exerts an equal and opposite force back on the first body.

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Newtonian gravitation is sometimes called universal mutual gravitation. Newton's third law points out that forces occur in pairs. If one body attracts another, the second body must also attract the first. Thus, gravitation is mutual. Furthermore, gravity is universal. That is, all objects with mass attract all other masses in the universe. The **mass** of an object is a measure of the amount of matter or "stuff" in the object, usually expressed in kilograms. You may be used to thinking of "massive" objects as very large objects. However, in science massive objects are those that contain a lot of matter. They may or may not be large. For example, a two-centimetre ball of lead is more massive than a large balloon full of air. In everyday life, the terms mass and weight are used interchangeably. When you report your weight at the doctor's office as 60 kg you are actually reporting your mass. In science, mass is not the same as **weight**. Mass is an intrinsic property of an object and is the same no matter what forces are acting on an object. An object's weight is the force that gravity exerts on the object. An object in space far from Earth's gravitational force would have no weight, but it would contain the same amount of matter and would have the same mass that it has on Earth.

Newton found that the gravitational force of attraction between two objects is directly proportional to the product of the masses of the two objects. For example, doubling one of the masses would double the gravitational force, and doubling both masses would quadruple the force. Newton also realized that the distance between the objects is important. In other words, the gravitational force between two bodies depends not only on the masses of the bodies but also on the distance between them. He recognized that the force of gravity decreases as the square of the distance between the objects increases. Specifically, if the distance from, say, Earth to the Moon were doubled, the gravitational force between them would decrease by a factor of 2^2, or 4. If the distance were tripled, the force would decrease by a factor of 3^2, or 9. This relationship is known as the **inverse square relation**. Newton guessed that gravity works by an inverse square relation because he had already discovered that light behaves this way (discussed in Chapter 6).

mass A measure of the amount of matter making up an object.

weight The force that gravity exerts on an object.

inverse square relation A rule that the strength of an effect (such as gravity) decreases in proportion as the distance squared increases.

To summarize, Newton's universal law of gravitation states that the force of gravity attracting two objects to each other equals a constant times the product of their masses divided by the square of the distance between the objects. Gravity is universal: Your mass affects the planet Neptune and the galaxy M31, and every other object in the universe, and their masses affect you—although not much, because they are so far away and your mass is relatively very small. (Refer to **Newton's Laws of Motion and Gravitation** in the Math Reference Cards.)

Orbital Motion

Newton's laws of motion and gravitation make it possible for you to understand why and how the Moon orbits Earth and the planets orbit the Sun, and to discover why Kepler's laws work. To understand how an object can orbit another object, you need to see orbital motion as Newton did. Begin by studying **Visualizing Astronomy 3.2, Orbiting Earth,** and notice three important ideas:

1. An object orbiting Earth, and any orbiting object, is actually falling (being accelerated due to gravitational force) toward Earth's centre. An object in a stable orbit continuously misses Earth because of its horizontal velocity.
2. Objects orbiting each other actually revolve around their mutual centre of mass.
3. Notice the difference between closed orbits and open orbits. If you want to leave Earth never to return, you must give your spaceship a high enough velocity so it will follow an open orbit.

When the captain of a spaceship says to the pilot, "Put us into a circular orbit," the ship's computers must quickly calculate the velocity needed to achieve a circular orbit. That circular velocity depends only on the mass of the planet and the distance from the centre of the planet. Once the engines fire and the ship reaches circular velocity, the engines can shut down. The ship is in orbit and will fall around the planet forever, as long as it is above the atmosphere's friction. No further effort is needed to maintain orbit, in keeping with the laws Newton discovered. (Refer to **Circular Velocity** in the Math Reference Cards.)

Newton's laws of motion and his universal theory of gravitation enabled him to explain Kepler's laws of planetary motion. Kepler's first law—that the planets move in elliptical orbits—is a direct result of the inverse square law of gravitation. Newton proved that any object moving in a closed orbit according to the inverse square law must follow an elliptical path. Furthermore, just like the spaceship in stable orbit around Earth, the planets, the Moon, and all objects in the universe will remain on their

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respective paths forever unless an external force (such as a collision with another object) acts on them.

Newton's law of gravitation also explains Kepler's second law, which states that planets move faster when they are closer to the Sun in their orbits (refer to Table 3.1). To understand this, you must first understand that a measure of a planet's rotational motion is its angular momentum, which is proportional to its velocity and its distance from the Sun. As a result of Newton's laws, in the absence of additional rotational forces the total angular momentum of a planet is conserved (remains constant). When a planet's distance from the Sun increases, it moves slower to balance out the increased distance, and vice versa, to keep the angular momentum constant. The change in motion with distance from the Sun results in equal areas being swept out by the planet in equal amounts of time, as described in Kepler's second law (see Figure 3.13). You can observe the conservation of angular momentum for yourself by watching an ice skater spinning on the ice. She can increase or decrease how fast she rotates by pulling her arms in or spreading them out and in this way she increases or decreases her "distance" from her axis of rotation.

Newton was also able to combine his laws of motion with the law of gravitation to derive a relationship between a planet's orbital period and its average distance from the Sun, which was identical to Kepler's third law. You can now understand the power of Newton's work. He was able to explain all the patterns of planetary motion observed by Kepler by using very simple and universal rules. But this was not all. Gravity is also the key to understanding another critical phenomenon on Earth: ocean tides.

Tides: Gravity in Action

Newton understood that gravity is mutual—Earth attracts the Moon, and the Moon attracts Earth—and that means the Moon's gravity can explain the ocean tides. But Newton also realized that gravitation is universal, and that means there is much more to tides than simply Earth's oceans.

Tides are caused by small differences in gravitational force. As Earth and the Moon orbit around each other, they attract each other gravitationally. Because the side of Earth toward the Moon is a bit closer, the Moon pulls on it more strongly and that pulls up a bulge. Also, the Moon pulls on the near side of Earth a bit more than it pulls on Earth's far side and that produces a bulge on the far side (Figure 3.19). The oceans are deeper in these bulges, and as Earth rotates and carries you into a bulge, you see the tide creeping up the beach. Because

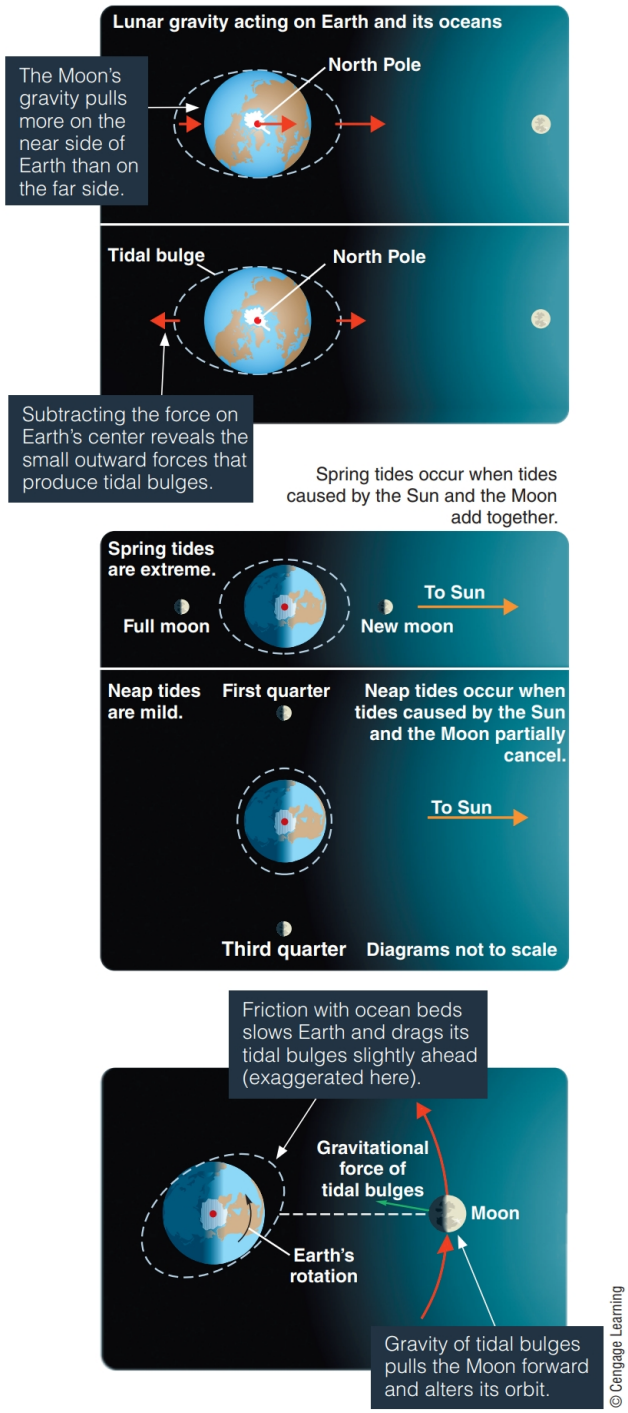


Figure 3.19 Tides are produced by small differences in the gravitational force exerted on different parts of an object. The side of Earth nearest the Moon feels a larger force than the side farthest away. Relative to Earth's centre, small forces are left over, and they cause the tides. Both the Moon and the Sun produce tides on Earth. Tides can alter both an object's rotation and orbital motion.

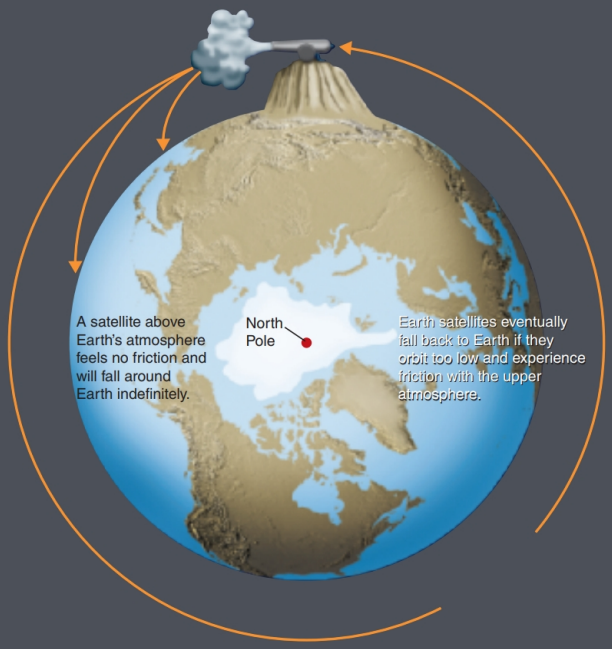
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Visualizing Astronomy 3.2

ORBITING EARTH

1

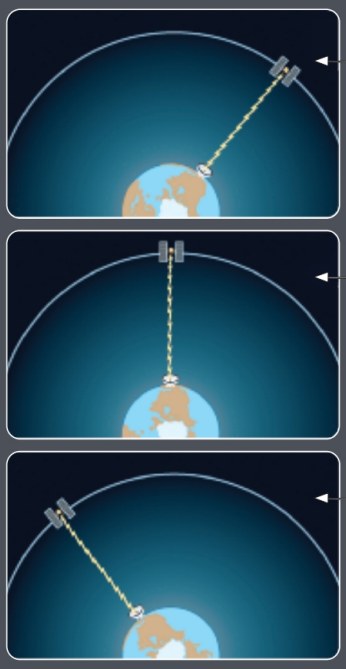
You can understand orbital motion by thinking of a cannonball moving around Earth in a circular path. Imagine a cannon on a high mountain aimed horizontally as shown at right. A little gunpowder gives the cannonball a low velocity, and it doesn't travel very far before falling to Earth. More gunpowder gives the cannonball a higher velocity, and it travels farther. With enough gunpowder, the cannonball travels so fast it never strikes the ground. Earth's gravity pulls it toward Earth's centre, but Earth's surface curves away from it at the same rate it falls. It is in orbit. The velocity needed to stay in a circular orbit is called **circular velocity**. Just above Earth's atmosphere, at an altitude of 200 km, circular velocity is 7790 m/s and the orbital period is about 88 minutes.



1a

A **geosynchronous satellite** orbits eastward with the rotation of Earth and remains above a fixed spot on the equator, which is ideal for communications and weather satellites.

A Geosynchronous Satellite



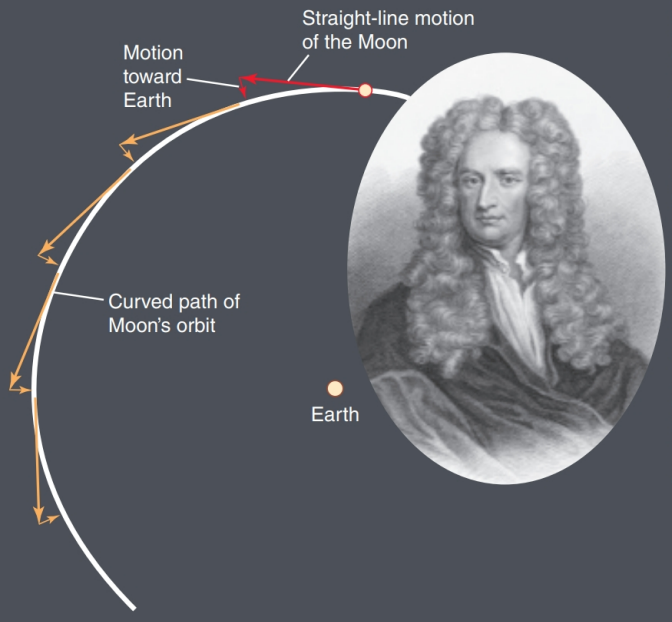
At a distance of 42 230 km from Earth's centre, a satellite orbits with a period of 24 hours.

The satellite orbits eastward, and Earth rotates eastward under the moving satellite.

The satellite remains fixed above a spot on Earth's equator.

1b

According to Newton's first law of motion, the Moon should follow a straight line and leave Earth forever. Because it follows a curve, Newton knew that some force must continuously accelerate it toward Earth, gravity. Every second the Moon moves 1020 m eastward and falls about 1.4 mm toward Earth. The combination of these motions produces the Moon's curved orbit. The Moon is falling all the time.



Engraved by Freeman and published in Lives of Eminent and Illustrious Englishmen, United Kingdom, 1830. Georgios Kollidas / Shutterstock.com

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1c

Astronauts in orbit around Earth feel weightless, but they are not—to use a term from old science fiction movies—"beyond Earth's gravity." Like the Moon, the astronauts are accelerated toward Earth by Earth's gravity, but they travel fast enough along their orbits that they continually "miss the Earth." They are literally falling around Earth. Inside or outside a spacecraft, astronauts feel weightless because they and their spacecraft are falling at the same rate. Rather than saying they are weightless, you should more accurately say they are in free fall.



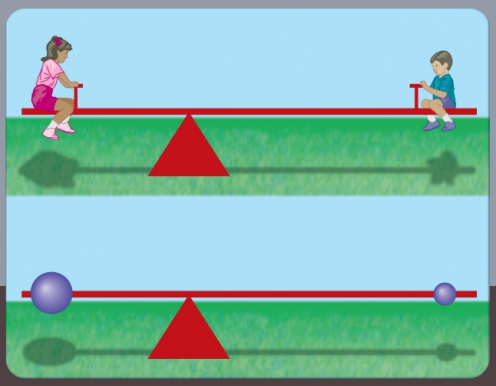
NASA

2

To be accurate you should not say that an object orbits Earth. Rather, the two objects orbit each other. Gravitation is mutual, and if Earth pulls on the Moon, the Moon pulls on Earth. The two bodies revolve around their common **centre of mass**, the balance point of the system.

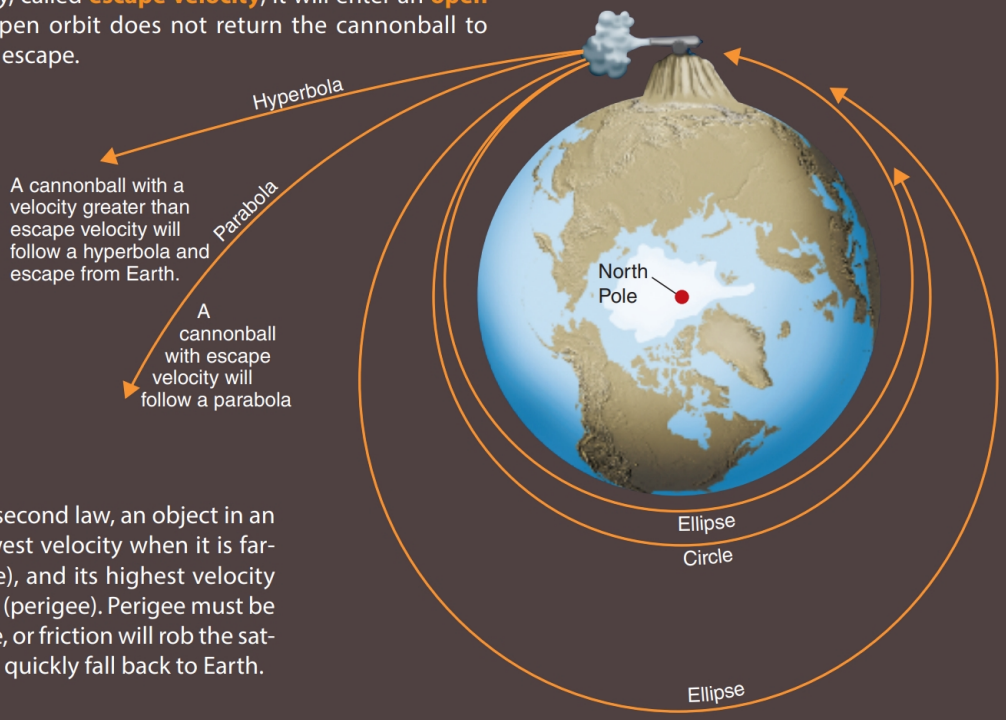
2a

Two bodies of different mass balance at their centre of mass, which is located closer to the more massive object. As the two objects orbit each other, they revolve around their common centre of mass as shown at right. The centre of mass of the Earth–Moon system lies only 4670 km from the centre of Earth—inside Earth. As the Moon orbits the centre of mass on one side, Earth swings around the centre of mass on the opposite side.



3

Closed orbits are repeating cycles. The Moon and artificial satellites orbit Earth in closed orbits. Below, the cannonball could follow an elliptical or a circular **closed orbit**. If the cannonball travels at the velocity needed to leave Earth permanently, called **escape velocity**, it will enter an **open orbit**. An open orbit does not return the cannonball to Earth; it will escape.



3a

As described by Kepler's second law, an object in an elliptical orbit has its lowest velocity when it is farthest from Earth (apogee), and its highest velocity when it is closest to Earth (perigee). Perigee must be above Earth's atmosphere, or friction will rob the satellite of energy and it will quickly fall back to Earth.

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HOW DO WE KNOW? 3.4



Testing a Theory by Prediction

When you read about any science, notice that scientific theories face in two directions. They look back into the past and explain previously observed phenomena. For example, Newton's laws of motion and gravity explained how the planets moved. But theories also face forward in that they enable you to make predictions about what you should find as you explore further. Newton's laws allowed astronomers to calculate the orbits of comets, predict their return, and eventually understand their origin.

Scientific predictions are important in two ways. First, if a theory leads to a prediction and scientists later discover the prediction was true, the theory is confirmed, and scientists gain confidence that it is a true description of nature. But predictions are important in science in a second way. Using an existing theory to make a prediction may lead you into an unexplored avenue of knowledge. For example, the first theories of genetics made predictions that confirmed the genetic theory of inheritance, but those predictions also created a new understanding of how living creatures evolve.

As you read about any scientific theory, think about both what it can explain and what it can predict.

there are two bulges, there are two high tides each day, although the exact pattern of tides at any given locality depends on details such as ocean currents, the shape of the shore, and so on.

The Sun also produces tides on Earth, although they are smaller than lunar tides. At new and full moons, the lunar and solar tides add together to produce extra high and extra low tides that are called **spring tides**. At first- and third-quarter moons, the solar tides cancel out part of the lunar tides so that high and low tides are not extreme (see Figure 3.19). These are called **neap tides**.

Whereas the oceans flow easily into tidal bulges, the nearly rigid bulk of Earth flexes into tidal bulges, and the plains and mountains rise and fall a few centimetres twice a day. Friction is gradually slowing Earth's rotation, and fossil evidence shows that Earth used to rotate faster. In the same way, Earth's gravity produces tidal bulges in the Moon, and, although the Moon used to rotate faster, friction has slowed it down, and it now keeps the same side facing Earth.

Tides can also affect orbits. The rotation of Earth drags the tidal bulges slightly ahead of the Moon, and the gravitation of the bulges of water pull the Moon forward in its orbit. This makes the Moon's orbit grow larger by about 4 cm a year, an effect that astronomers can measure by bouncing lasers off reflectors left on the Moon by the Apollo astronauts.

spring tide Ocean tide of large range that occurs at full and new moon.

neap tide Ocean tide of small range occurring at first- and third-quarter moon.

Universal Motion

Newton's insights gave the world a new conception of nature. His laws of motion were *general* laws that described the motions of *all* bodies under the action of external forces. Just imagine: A few simple laws that can explain how your car accelerates, how the Canadian hockey team manoeuvres on ice, and even how the planets move! And furthermore, Newton's laws and the theory of gravitation allow us to break the bonds of Earth and the solar system and understand the motion of all objects in the universe. As you will see in later chapters, we can detect planets around other stars by observing the motion of the star as it gravitationally interacts with any planets orbiting it. We can calculate the mass of these new planets using the law of gravitation. Indeed, this has been used to calculate the mass of Earth and all other planets, and the Sun. We can even detect black holes at the centre of galaxies by observing the motion of objects around it.

The story of the development of astronomy that you have just read is also the story of the development of the scientific method. Ancient astronomers began the process by carefully gathering and recording data. Gradually, models were developed that best fit the data and over time they were tested against observations and discarded if necessary. Good scientific theories are those that can make a broad range of predictions that can be confirmed against observations, and that can provide new insight into nature. Science and astronomy today progress through the careful

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application of this method of studying nature. As the 1915 Nobel Prize-winning physicist Sir William Lawrence Bragg said, "The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them." Sometimes this requires a huge leap of imagination and a questioning of our most strongly held beliefs. The shift from the geocentric to the heliocentric viewpoint was a harsh lesson in humility for humanity. Earth became merely another planet orbiting the Sun. But this first revolution of thought started us on a fantastic journey of scientific discovery. The efforts of Newton and his predecessors, all the way back to our ancient ancestors, opened the door to our modern way of scientific thinking and our current understanding of the universe.

The **Big Picture**

Astronomy is one of the oldest and most universally practised sciences. Ancient civilizations all over the world observed the Sun, the Moon, and the stars for timekeeping, for agricultural planning, for religious and ceremonial purposes, and for navigation. Early models of the universe placed Earth in a special place, at rest in the centre of the universe. Based on observations and preliminary hypotheses of ancient astronomers, a heliocentric model of the universe was proposed. This new theory stimulated people to see Earth and humanity as part of an elegant and complex universe.

We are not in a special place ruled by mysterious planetary forces: Kepler showed that the planets move according to simple rules. Newton found laws that account for the fall of an apple, the ocean tides, and orbital motion. Earth, the Sun, and all of humanity are part of a universe whose motions can be described by a few fundamental laws of motion and gravity. And those simple rules open the universe to scientific study. Astronomy tells us that we are special because we can study the universe and eventually understand what we are.

Review and **Discussion Questions**

Review Questions

1. What did ancient astronomers observe, and how did it affect their society?
2. Why did Greek astronomers conclude that the heavens were made up of perfect spheres moving at constant?
3. Why did early astronomers conclude that Earth had to be motionless?
4. How did the Ptolemaic model explain retrograde motion?
5. In what ways were the models of Ptolemy and Copernicus similar?
6. What is the difference between the Copernican hypothesis and the Copernican model? Why did the Copernican hypothesis win gradual acceptance?
7. Explain how Kepler's laws contradict uniform circular motion.
8. How do a hypothesis, a theory, and a law differ?
9. Review Galileo's telescopic discoveries and explain why they supported the heliocentric model and contradicted the geocentric model.
10. Explain why you might describe the orbital motion of the Moon with the statement, "The Moon is falling."
11. If you lived on Mars, which planets would describe retrograde loops? Which would always be seen near the Sun? Which would never be visible as crescent phases?
12. **How Do We Know?** How does a paradigm affect the questions you ask and the answers you find acceptable?
13. **How Do We Know?** How would you respond to someone who said, "Oh, that's only a theory."
14. **How Do We Know?** Why would it be appropriate to refer to evidence as the "reality checks" in science?

Discussion Questions

1. How has science influenced society and how has society influenced science?

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Learning to Look

1. What three astronomical objects are represented on this excerpted image from a postage stamp? What are the two rings?



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2. Why can the object shown below be bolted in place and used 24 hours a day without adjustment?



zhannaprokopeva / Shutterstock.com

3. Why is it a bit misleading to say that this astronaut is weightless?



NASA/JSC

STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *The Origin of Modern Astronomy.*

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
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THIS PHOTO OF EARTH was taken by the *Lunar Reconnaissance Orbiter* spacecraft in 2017 as it orbited the Moon. The shadowy lunar horizon is visible in the foreground. This image recalls a similar photograph, called "Earthrise," taken by the crew of *Apollo 8* in 1968 as they, too, orbited the Moon. Photos like these help us understand our place in the cosmos. We can appreciate the beauty and fragility of our planet when we see it hovering in the near-vacuum of space, viewed by a robot flying over a barren lunar landscape.

NASA Goddard

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PART ONE

4 Astronomical Telescopes and Instruments: Extending Humanity's Vision

CHAPTER OUTLINE

4.1 Radiation: Information from Space
4.2 Telescopes
4.3 Observatories on Earth: Optical and Radio
4.4 Astronomical Instruments and Techniques
4.5 Airborne and Space Observatories

GUIDEPOST

In earlier chapters, you looked at the sky the way ancient astronomers did, with the unaided eye, and had a glimpse through Galileo's telescope, which revealed wonderful things about the Moon, Jupiter, and Venus. Now you can study the telescopes, instruments, and techniques of the modern astronomer. Astronomy is almost entirely an observational science. Astronomers cannot visit distant galaxies and far-off worlds, so they must observe celestial objects using astronomical telescopes.

This chapter will help you answer the following questions:

- What is light?
- How do telescopes work? What are their capabilities and limitations?
- How are observatories built, and how are good locations chosen for them?
- What kinds of instruments and techniques do astronomers use to record and analyze light?
- Why do astronomers sometimes use X-ray, ultraviolet, and infrared telescopes, and why must these types of telescopes operate in the upper atmosphere or in orbit?

Light is a treasure that links us to the sky. An astronomer's quest is to gather as much light as possible from the Moon, the Sun, planets, stars, and galaxies in order to extract information about their natures. Telescopes, which gather and focus light for analysis, can help do that. Nearly all the interesting objects in the sky are very faint sources



JPL, NASA/CXC/JPL-Caltech/STScI/NSF/NRAO/VLA

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Image of NGC 4258 features X-rays from Chandra (blue), radio waves from the VLA (purple), optical data from Hubble (grey), and infrared from Spitzer (red).

The immense distances to the stars and the galaxies mean that we see everything in space in the past, some as they were before the Earth came to be. Telescopes are time machines.

Carl Sagan

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of light, so large telescopes like the one in Figure 4.1 are built to collect the greatest amount of light possible. This chapter's discussion of astronomical research concentrates on large telescopes and the special instruments and techniques used to analyze light. An optical telescope gathers visible light, but visible light is only one type of radiation arriving here from distant objects. Astronomers can extract information from other forms of radiation by using other types of telescopes. Radio telescopes, for example, give an entirely different view of the sky. Some of these specialized telescopes can be used from Earth's surface, but others must be placed high in Earth's atmosphere or even above it.

4.1 Radiation: Information from Space

Modern astronomers analyze light using sophisticated instruments and techniques to investigate the compositions, motions, internal processes, and evolution of celestial objects. To understand this, you need to learn about the nature of light.

Light as a Wave and as a Particle

Have you ever noticed the colours in a soap bubble? If so, you have seen one effect of light behaving as a wave. When that same light enters the light meter on a camera, it behaves as a particle. How light behaves depends on how you treat it—light has both wave-like and particle-like properties. Sound is another type of wave that you have already experienced. Sound waves are air pressure disturbances of air molecules that travel from a source to the ear. Sound requires a solid, liquid, or gas medium to carry it; so, for example, in space outside a spacecraft there can be no sound. In contrast, light is composed of a combination of electric and magnetic waves that can travel through empty space. Unlike sound, light waves do not require a medium and thus can travel through a vacuum.

electromagnetic radiation Changing electric and magnetic fields that travel through space and transfer energy from one place to another; examples are light or radio waves.

wavelength The distance between successive peaks or troughs of a wave, usually represented by a lowercase Greek lambda, λ.

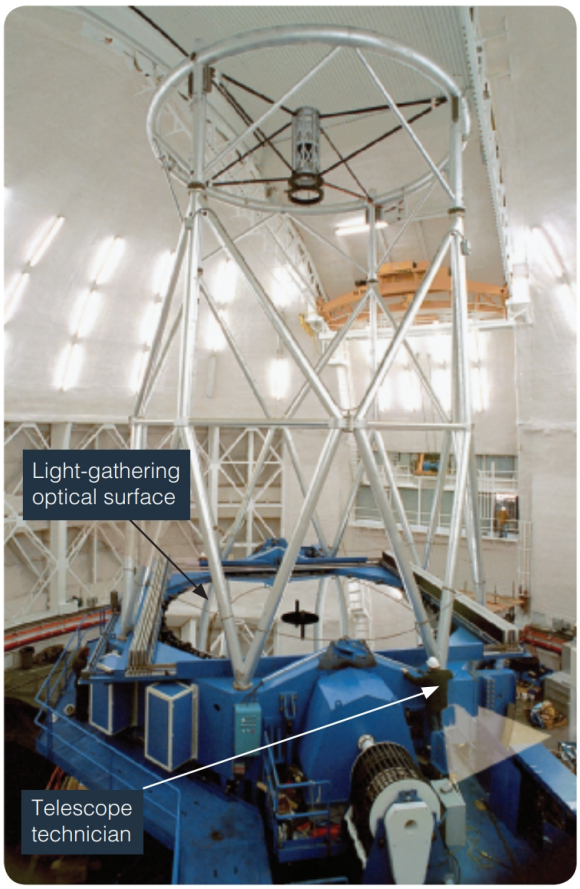


Figure 4.1 The northern Gemini telescope in Mauna Kea, Hawaii, stands over 19-m high when pointed straight up.

Because light is made up of both electric and magnetic fields, it is referred to as **electromagnetic radiation**. Visible light is only one form of electromagnetic radiation. Electromagnetic radiation is a wave phenomenon—that is, it is associated with a periodically repeating disturbance (a wave) that carries energy. Imagine waves in water: If you disturb a pool of water, waves spread across the surface. Now imagine placing a ruler along the travel direction of the wave. The distance between peaks is the **wavelength**. (Refer to **Wave Properties** in the Math Reference Cards.) The changing electric and magnetic fields of electromagnetic waves travel through space at about 300 000 kilometres per second. That is 1 billion kilometers per hour. This is commonly referred to as the speed of light, but it is the speed of all electromagnetic radiation.

It may seem odd to use the word *radiation* when talking about light, but radiation really refers to anything that spreads outward from a source. Light radiates from a source, so you can correctly refer to light as a form of radiation.

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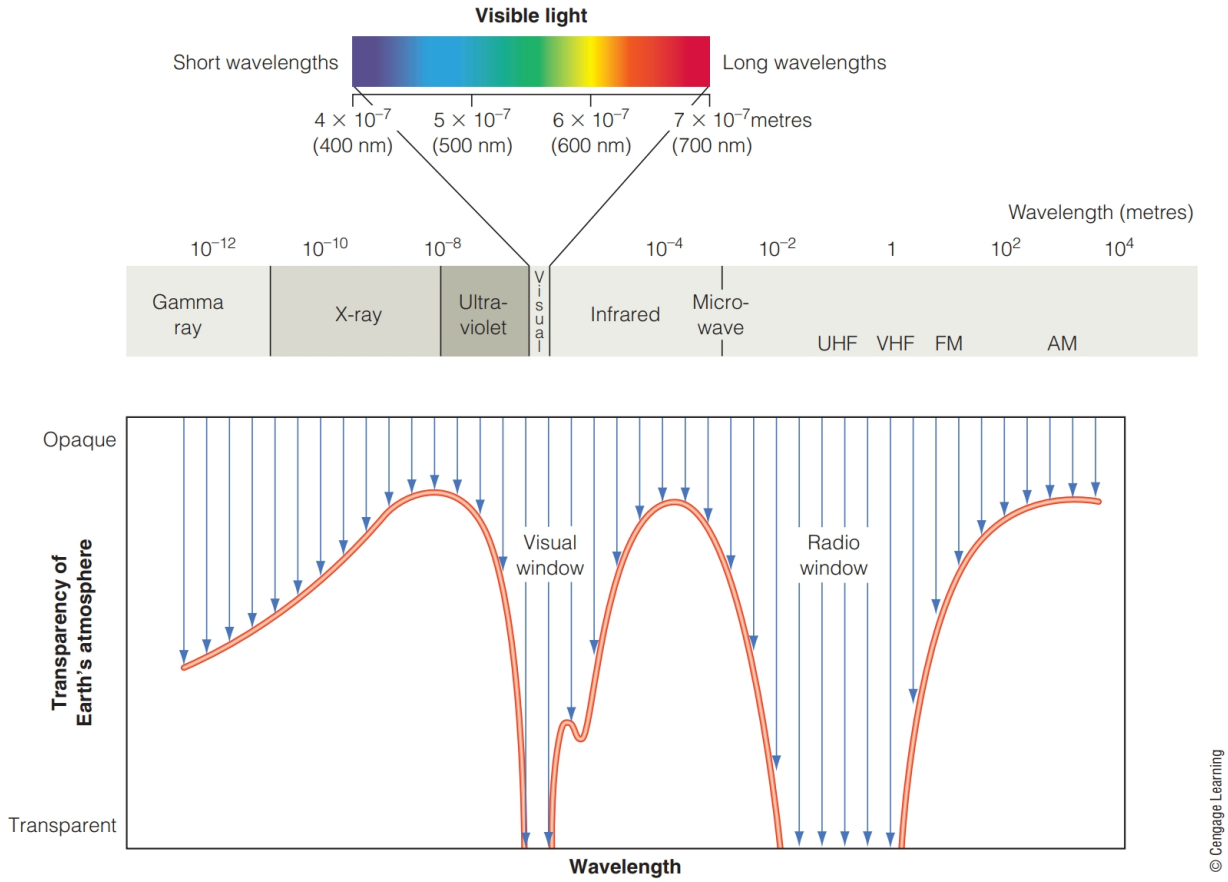


Figure 4.2 The spectrum of visible light, extending from red to violet, is only part of the electromagnetic spectrum. The lower panel shows that most radiation is absorbed in Earth's atmosphere, and only radiation with certain wavelengths, such as the visual and radio windows, can easily reach Earth's surface.

The Electromagnetic Spectrum

The electromagnetic spectrum is simply the types of electromagnetic radiation arranged in order of increasing wavelength. Rainbows are spectra (plural) of visible light. The colours of visible light have different wavelengths: Red has the longest wavelength and violet the shortest, as shown in the visible spectrum at the top of Figure 4.2.

The average wavelength of visible light is about 0.0005 mm. One hundred light waves would fit end-to-end across the thickness of a sheet of paper. It is too awkward to measure such short distances in millimetres, so physicists and astronomers describe the wavelength of light using either the unit of the nanometre (nm), one-billionth of a metre (10^{-9} m), or the angstrom (Å), equal to 10^{-10} m or 0.1 nm. The wavelength of visible light ranges between about 400 nm and 700 nm, or, equivalently, 4000 Å and 7000 Å. Infrared astronomers often refer to wavelengths using units of microns (10^{-6} m), while radio astronomers use millimetres, centimetres, or metres. Figure 4.2 shows how the visible spectrum makes up only a small part of the electromagnetic spectrum.

Beyond the red end of the visible range lies **infrared (IR)** radiation, with wavelengths ranging from 700 nm to about 1 mm. In the beginning of the 19th century, English astronomer William Herschel discovered that sunlight contained radiation that is detectable by thermometers but not by human eyes. He named that invisible light "infrared," meaning "below red." Your eyes are not sensitive to this radiation, but your skin can sense some of it as heat. A heat lamp

infrared (IR) The portion of the electromagnetic spectrum with wavelengths longer than red light, ranging from 700 nm to about 1 mm, between visible light and radio waves.

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Figure 4.3 This example shows a dog in visible or regular light (left) and infrared light, with the scale for de-coding temperature on the right.

is nothing more than a bulb that gives off large amounts of infrared radiation. False colours assigned to different temperatures allow us to visualize the wavelengths the human eye does not see (Figure 4.3).

Radio waves have even longer wavelengths than IR radiation. The radio radiation used for AM radio transmissions has wavelengths of a few hundred metres, while FM, television, and also military, governmental, and amateur radio transmissions have wavelengths from a few tens of centimetres to a few tens of metres. Microwave transmissions, used for radar and long-distance telephone communications, have wavelengths from about 1 millimetre to a few centimetres.

ultraviolet (UV) The portion of the electromagnetic spectrum with wavelengths shorter than violet light, between visible light and X-rays.

X-rays Electromagnetic waves with wavelengths shorter than ultraviolet light.

gamma rays The shortest-wavelength electromagnetic waves.

photon A quantum of electromagnetic energy that carries an amount of energy that increases proportionally with its frequency, but decreases proportionally with its wavelength.

atmospheric window Wavelength region in which our atmosphere is transparent—at visual, radio, and some infrared wavelengths.

Look at the electromagnetic spectrum in Figure 4.2 and notice electromagnetic waves with wavelengths shorter than violet light. They are called **ultraviolet (UV)**. Electromagnetic waves with wavelengths shorter than UV light are called **X-rays**, and the shortest are **gamma rays**.

The distinction between these wavelength ranges is mostly arbitrary—they are simply convenient human-invented labels. For example, the longest-wavelength infrared radiation and the shortest-wavelength microwaves are the same. Similarly, very short-wavelength ultraviolet light can be considered X-rays. Nonetheless, all these types of radiation are the same phenomenon as light. Some types your eyes can see, and some types your eyes can't see.

Although light behaves as a wave, under certain conditions it also behaves as a particle. A particle of light is called a **photon**, and you can think of a photon as a bundle of electromagnetic waves. The amount of energy a photon carries depends on the wavelength of a light wave. (Refer to **Wave Properties** in the Math Reference Cards.) Shorter-wavelength photons carry more energy, and longer-wavelength photons carry less energy. A photon of visible light carries a small amount of energy, but an X-ray photon carries much more energy, and a radio photon carries much less.

Astronomers are interested in electromagnetic radiation because it carries almost all available clues to the nature of planets, stars, and other celestial objects. Earth's atmosphere is opaque to most electromagnetic radiation, as shown by the graph at the bottom of Figure 4.2. Gamma rays, X-rays, and some radio waves are absorbed high in Earth's atmosphere, and a layer of ozone (O_3) at an altitude of about 30 km absorbs almost all UV radiation. Water vapour in the lower atmosphere absorbs long-wavelength IR radiation. Only visible light, some short-wavelength infrared radiation, and some radio waves reach Earth's surface through what are called **atmospheric windows**. To study the sky from Earth's surface, you must look out through one of these "windows" in the electromagnetic spectrum.

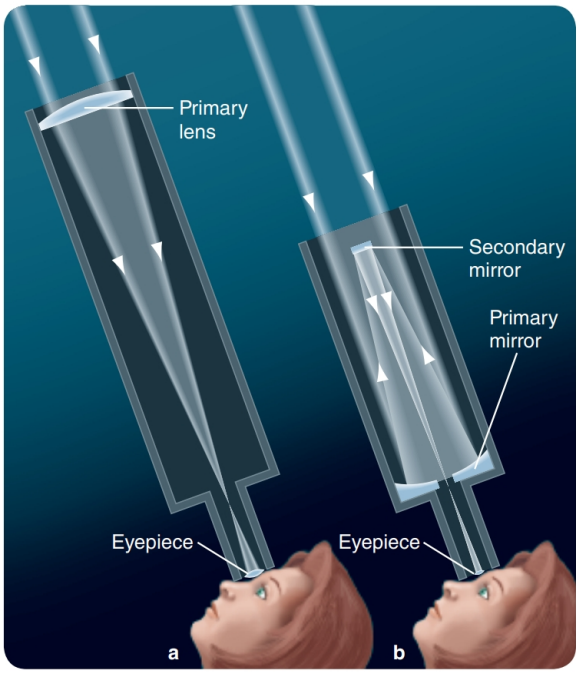
4.2 Telescopes

Astronomers build optical telescopes to gather light and focus it into sharp images. This requires careful optical and mechanical designs, and it leads astronomers to build very large telescopes. To understand that, you need to learn the terminology of telescopes, starting with the different types of telescopes and why some are better than others.

Two Kinds of Telescopes

Astronomical telescopes focus light into an image in one of two ways: either (1) a lens bends (refracts) the light as it passes through the glass and brings it to a focus to form an image, or (2) a mirror—a curved reflective surface—forms an image by bouncing light. Figure 4.4 demonstrates the difference between the two configurations. Because there are two ways to focus light, there

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Figure 4.4 (a) A refracting telescope uses a primary lens to focus starlight into an image that is magnified by another lens called an eyepiece. The primary lens has a long focal length, and the eyepiece has a short focal length. (b) A reflecting telescope uses a primary mirror to focus the light by reflection. In this particular reflector design, called a Cassegrain telescope, a small secondary mirror reflects the starlight back down through a hole in the middle of the primary mirror to the eyepiece lens.

Every large astronomical telescope built since 1900 has been a reflecting telescope. Mirrors are cheaper to make and easier to support than lenses. Moreover, mirrors do not suffer from so many optical distortions like lenses because light is reflected, it does not pass through the glass.

Optical telescopes gather visible light, but astronomers also build **radio telescopes** to gather radio radiation. Radio waves from celestial objects, just like visible light waves, penetrate Earth's atmosphere and reach the ground. You can see in Figure 4.5 how the dish reflector of a typical radio telescope focuses the radio waves so their intensity can be measured. Because radio wavelengths are so long, the disk reflector does not have to be as perfectly smooth as the mirror of a reflecting optical telescope.

refracting telescope A telescope that forms images by bending (refracting) light with a lens.

reflecting telescope A telescope that forms images by reflecting light with a mirror.

primary lens In a refracting telescope, the largest lens.

primary mirror In a reflecting telescope, the largest mirror.

eyepiece A short-focal-length lens used to enlarge the image in a telescope; the lens nearest to the eye.

focal length The focal length of a lens or mirror is the distance from that lens or mirror to the point where it focuses parallel rays of light.

optical telescope Telescope that gathers visible light.

radio telescope Telescope that gathers radio radiation.

are two types of astronomical telescopes. **Refracting telescopes** use a lens to gather and focus the light, whereas **reflecting telescopes** use a mirror.

The main lens in a refracting telescope is called the **primary lens**, and the main mirror in a reflecting telescope is called the **primary mirror**. Both kinds of telescopes form a small, inverted image that is difficult to observe directly, so a lens called the **eyepiece** is used to magnify the image and make it convenient to view. The **focal length** is the distance from a lens or mirror to the image it forms of a distant light source such as a star. Creating the proper optical shape to produce a good focus is an expensive process. The surfaces of lenses and mirrors must be shaped and polished to have no irregularities larger than the wavelength of light. Creating the optics for a large telescope can take months or years, involve huge precision machinery, and employ expert optical engineers and scientists.



ILYA GENKIN / Shutterstock.com

Figure 4.5 Famous Parkes Observatory telescope "The Dish," which broadcast television signal of Neil Armstrong and Buzz Aldrin stepping on the Moon on July 21, 1969. It is located in a remote part of Australia to be isolated from human-made radio frequency interference. In most radio telescopes a dish reflector concentrates the radio signal on the antenna. The signal is then amplified and recorded. For all but the shortest radio waves, wire mesh is an adequate reflector.

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The Powers of a Telescope

Astronomers struggle to build large telescopes because a telescope can help human eyes in three important ways: light gathering, resolving, and magnifying power. These are called the three powers of a telescope. The two most important of these three powers depend on the diameter of the telescope. (Refer to **The Powers of a Telescope** in the Math Reference Cards.)

Most celestial objects of interest to astronomers are faint, so you need a telescope that can gather large amounts of light to produce a bright image. **Light-gathering power** refers to the ability of a telescope to collect light. Catching light in a telescope is like catching rain in a bucket—the wider the bucket, the more rain it catches. The light-gathering power is proportional to the *area* of the primary mirror; that is, proportional to the square of the primary's diameter. A telescope with a diameter of 2 m has four times the light-gathering power of a 1-m telescope. That is why astronomers use large telescopes and why telescopes are ranked by their diameters. One reason why radio astronomers build big radio dishes is to collect enough radio photons, which have low energies, and concentrate them for measurement.

The **resolving power** refers to the ability of the telescope to reveal fine detail. One consequence of the wavelike nature of light is that there is an inevitable small blurring, due to a tendency of light to spread when it encounters edges of an obstacle, in this case telescope lens or a mirror. This is called diffraction. Every point of light in the image obtained by a telescope appears as a blurred disk surrounded by faint rings, called **diffraction fringes**, and you cannot see any detail smaller than the fringe (Figure 4.6). Astronomers can't eliminate diffraction fringes, but the fringes are smaller in larger telescopes, and that means they have better resolving power and can reveal finer detail (see **How Do We Know? 4.1**). For example, a 2-m telescope has diffraction fringes half as large and therefore two times better resolving power than a 1-m telescope. The size of the diffraction fringes also depends on wavelength, and at the long wavelengths of radio waves, the fringes are large and the resolving power is poor. That's another reason radio telescopes need to be larger than optical telescopes.

One way to improve resolving power is to connect two or more telescopes in an **interferometer**, which has a resolving power equal to that of a telescope as large as the maximum separation between the individual telescopes (Figure 4.7), a technique used in optical, infrared, and radio telescopes. The first interferometer was built in 1967, with Canadian radio telescopes at the Dominion Radio Astrophysical Observatory in Penticton, British Columbia and the Algonquin Radio Observatory at Traverse Lake in Ontario to simulate the resolution of a giant radio telescope measuring 3074 km, the physical distance between the two instruments.

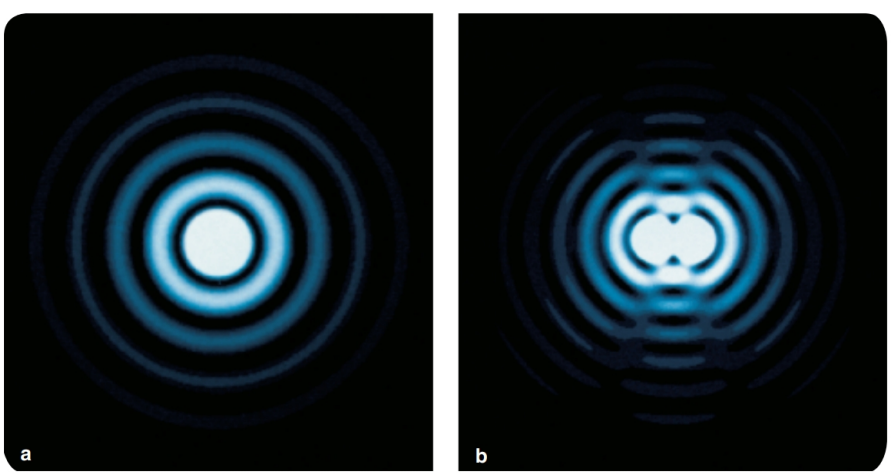
Aside from diffraction fringes, two other factors—optical quality and atmospheric conditions—limit resolving power. A telescope must contain high-quality optics to achieve its full potential resolving power. Even a large telescope shows little detail if its optical surfaces have imperfections. In addition, when you look through a telescope, you look through kilometres of turbulence in Earth's atmosphere, which makes images dance and blur, a condition

light-gathering power The ability of a telescope to collect light; proportional to the area of the telescope's objective lens or mirror.

resolving power The ability of a telescope to reveal fine detail; depends on the diameter of the telescope objective.

diffraction fringe Blurred fringe surrounding any image, caused by the wave properties of light. Because of this, no image detail smaller than the fringe can be seen.

interferometer Separated telescopes combined to produce a virtual telescope with the resolution of a much larger-diameter telescope.



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Figure 4.6 (a) Stars are so far away that their images are points, but the wavelike nature of light causes each star image to be surrounded with diffraction fringes, much magnified in this computer model. (b) Two stars close to each other have overlapping diffraction fringes and become difficult to detect separately.

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HOW DO WE KNOW? 4.1

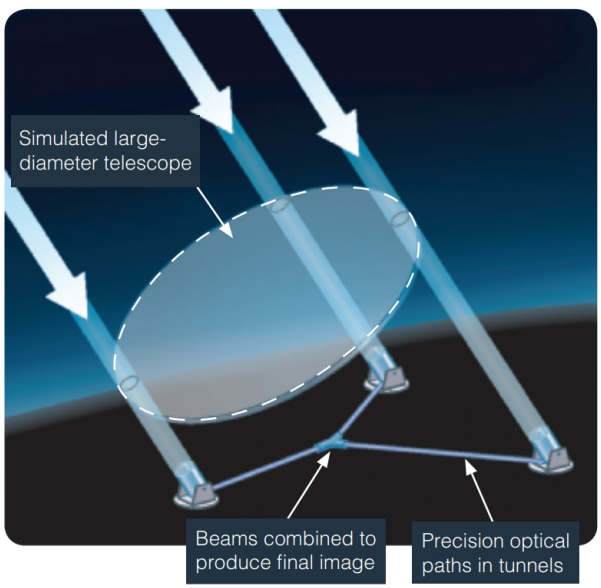


Resolving Power and the Accuracy of a Measurement

Have you ever seen a movie in which the hero magnifies a newspaper photo and reads some tiny detail? It isn't really possible, because newspaper photos are made up of tiny dots of ink, and no detail smaller than a single dot is visible no matter how much you magnify the photo. In fact, all images are made up of elements of some sort. In an image formed by a telescope, the size of the picture element is set by seeing or diffraction. It would be foolish to try to resolve (detect) any detail smaller than this limit.

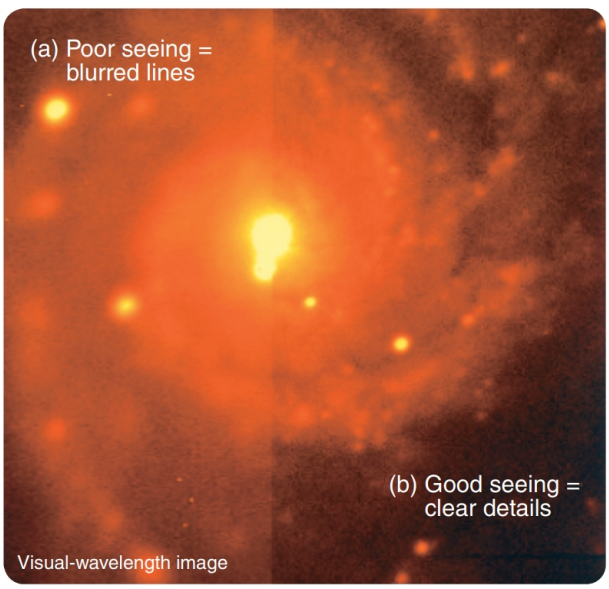
This limitation is true of all measurements in science. A zoologist might specify that a snake was 43.28932 cm long, and a sociologist might say that 98.2491 percent of people oppose drunk driving, but a critic might question the accuracy of those measurements. The resolution of the techniques may not justify the accuracy implied.

Science is based on measurement, and whenever you take a measurement, you should ask yourself how accurate that measurement can be and what its limits are.



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Figure 4.7 In an astronomical interferometer, light collected by smaller telescopes can be combined to simulate a larger telescope with a resolution determined by the separation of the smaller telescopes. This technique was developed first for radio telescopes and is now being applied to infrared and optical telescopes.



Courtesy William Keel

Figure 4.8 (a) The left half of this image of a galaxy is from a photograph recorded on a night of poor seeing. Small details are blurred. (b) The right half of this image is from a photo recorded on a night when the seeing was better—Earth's atmosphere above the telescope was steady. Much more detail is visible under good seeing conditions.

that astronomers call **seeing** (Figure 4.8). A related phenomenon is the twinkling of a star. The twinkles are caused by turbulence in Earth's atmosphere, and a star near the horizon, where you look through more air, twinkles more than a star overhead. On a night when the atmosphere is unsteady, the stars twinkle, the images are blurred, and the seeing is poor. A telescope performs best on a high mountaintop where the air is thin and steady, but even at good sites atmospheric turbulence spreads star images into blobs 0.5 to 1 arc seconds in diameter. That situation can be improved by a technique called **adaptive optics**, in which rapid computer calculations adjust the telescope optics and partly compensate for seeing distortions (Figure 4.9).

seeing Atmospheric conditions on a given night. When the atmosphere is unsteady, producing blurred images, the seeing is said to be poor.

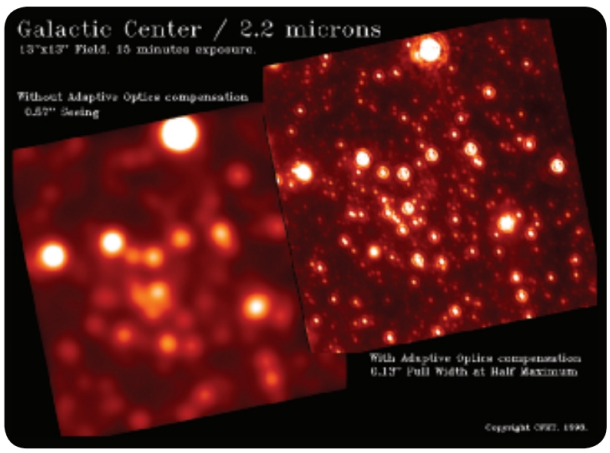
adaptive optics A computer-controlled optical system in an astronomical telescope used to partially correct for seeing.

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F. Kamphues/ESO

Figure 4.9a Laser beams (in the photo from the European Very Large Telescope, VLT, at Paranal Observatory in Chile) create artificial stars in the night sky. The light of a star is analyzed by a computer that corrects the shape of the adaptive mirror for the atmosphere's blurring effects. The colour of the laser is precisely tuned to energize a layer of sodium atoms found in one of the upper layers of the atmosphere, thought to be a leftover from meteorites entering Earth's atmosphere. When excited by the light from the laser, the atoms start glowing, forming a small bright spot that can be used as an artificial reference star for the adaptive optics.



© Canada-France-Hawaii Telescope

Figure 4.9b The Canada–France–Hawaii Telescope (CFHT), Mauna Kea, Hawaii, was one of the first in the world to use adaptive optics. This image shows the galactic centre region without (left) and with adaptive optics (right).

magnifying power The ability of a telescope to make an image larger.

Even with adaptive optics, there is an intrinsic limitation on the information in an image related to the accuracy of a measurement. All measurements have some built-in uncertainty, and scientists must learn to work within those limitations.

The third—and, you may be surprised to learn, least important—power of a telescope is **magnifying power**, the ability to make an image large. The magnifying power of a telescope with an eyepiece equals the focal length of the primary mirror or lens divided by the focal length of the eyepiece. For example, a telescope with a primary mirror that has a focal length of 700 mm and an eyepiece with a focal length of 14 mm has a magnifying power of 50. Higher magnifying power does not necessarily show you more detail because the amount of detail you can see in practice is limited by a combination of the seeing conditions and the telescope's resolving power and optical quality.

A telescope's primary function is to gather light and thus make faint things appear brighter, so the light-gathering power is the most important power and the diameter of the telescope is its most important characteristic. Light-gathering power and resolving power are fundamental properties of a telescope that cannot be altered, whereas magnifying power can be changed simply by changing the eyepiece. (Refer to **The Powers of a Telescope** in the Math Reference Cards.)

4.3 Observatories on Earth: Optical and Radio

Most major observatories are located far from big cities and usually on high mountains. Optical astronomers avoid cities because light pollution, the brightening of the night sky by light scattered from artificial outdoor lighting, can make it impossible to see faint objects. In fact, many residents of cities are unfamiliar with the beauty of the night sky because they can see only the brightest stars. Radio astronomers face a problem of radio interference analogous to light pollution. Weak radio signals from the cosmos are easily drowned out by human radio interference—everything from automobiles with faulty ignition systems to poorly designed transmitters in communication. To avoid that, radio astronomers locate their telescopes as far from civilization as possible. Hidden deep in mountain valleys, they are able to observe the sky protected from human-made radio noise.

Astronomers prefer to place optical telescopes on mountains because the air there is thin and more transparent, but, most importantly, they carefully select mountains where the airflow is usually not turbulent so the seeing is good. Building an observatory on top of a high mountain far from civilization is difficult and expensive, but the dark sky and good seeing make it worth the effort.

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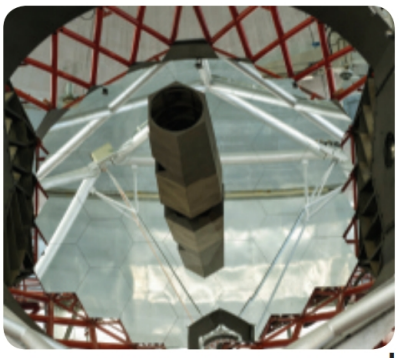
Figure 4.10 (a) The four telescopes of the European Very Large Telescope (VLT) are housed in separate domes at Paranal Observatory in Chile. (b) The Gran Telescopio Canarias (GTC) on La Palma in the Canary Islands contains 36 hexagonal mirror segments in its 10.4-m primary mirror. (c) New generation of large telescopes. All will be supported by adaptive optics, multiple laser guide star units, and large science instruments.



ESO/G. Hüdepohl (atacamaphoto.com)



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Courtesy TMT International Observatory



Giant Magellan Telescope - GMTO Corporation



ESO/L. Calçada



Name	Thirty Meter Telescope	Giant Magellan Telescope	European Extremely Large Telescope
Date	Late-2020s Projected Operation	Mid-2020s Projected Operation	Mid-2020s Projected Operation
Location	TBA	TBA	Chile
Resolution	12X Hubble Resolution	10X Hubble Resolution	16X Hubble Resolution
Mirror diameter	30 m	25.5 m	39.3 m

Credit for new image: lunamarina / Shutterstock.com

c

Study **Visualizing Astronomy 4.1, Modern Astronomical Telescopes**, and notice two important points:

1. Research telescopes must focus their light to positions at which cameras and other instruments can be placed.
2. Small telescopes can use other focal arrangements that would be inconvenient in larger telescopes.

Telescopes located on the surface of Earth, whether optical or radio, must move continuously to stay pointed at a celestial object as Earth turns on its axis. This is called **sidereal tracking** (*sidereal* refers to the stars).

The days when astronomers worked beside their telescopes through long, dark, cold nights are nearly gone. The complexity and sophistication of telescopes require a battery of computers, and almost all research telescopes are run from warm control rooms.

High-speed computers have allowed astronomers to build new, giant telescopes with unique designs. The European Southern Observatory has built the Very Large Telescope (VLT) high in the remote Andes Mountains of northern Chile. The VLT consists of four telescopes, each with a computer-controlled mirror 8.2 m in diameter and only 17.5 cm thick (Figure 4.10a). The four telescopes can work singly or can combine their light to work as one large telescope to have the effective diameter of a 100-m telescope. The Gran Telescopio Canarias, located atop a volcanic peak in the Canary Islands in Spain, carries a segmented mirror 10.4 m in diameter and holds, for the moment, the record as the largest single telescope in the world (Figure 4.10b). Other giant telescopes are being planned with innovative designs (Figure 4.10c).

sidereal tracking The continuous movement of a telescope to keep it pointed at a star as Earth rotates.

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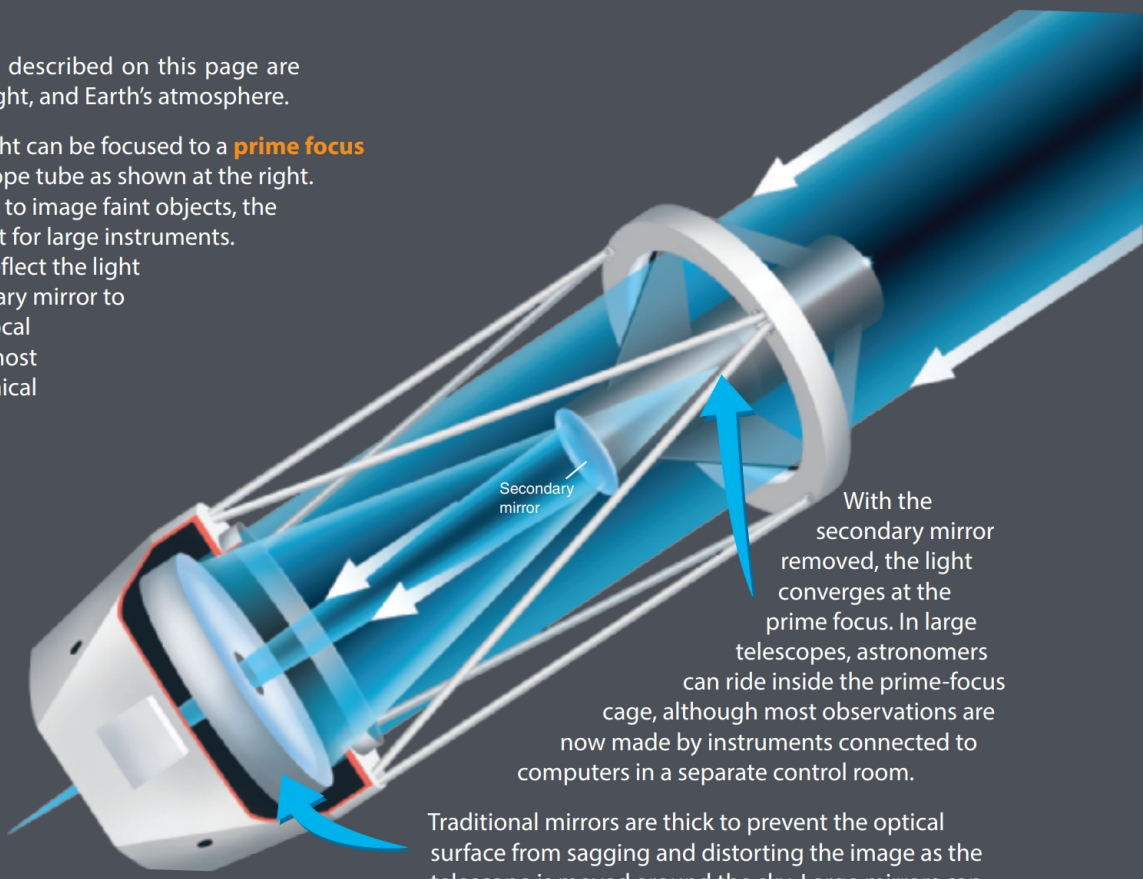
Visualizing Astronomy 4.1

MODERN ASTRONOMICAL TELESCOPES

1

The traditional telescopes described on this page are limited by complexity, weight, and Earth's atmosphere.

In larger telescopes, the light can be focused to a **prime focus** position high in the telescope tube as shown at the right. Although it is a good place to image faint objects, the prime focus is inconvenient for large instruments. A **secondary mirror** can reflect the light through a hole in the primary mirror to a **Cassegrain focus**. This focal arrangement may be the most common form of astronomical telescope.



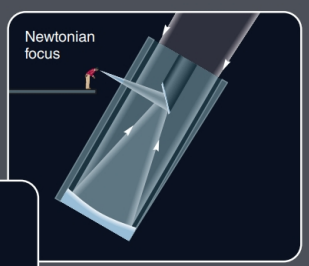
With the secondary mirror removed, the light converges at the prime focus. In large telescopes, astronomers can ride inside the prime-focus cage, although most observations are now made by instruments connected to computers in a separate control room.

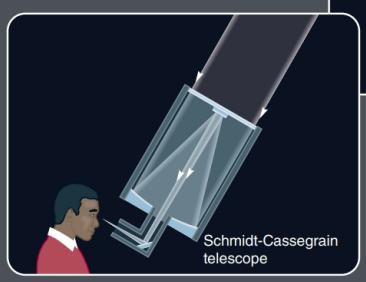
The Cassegrain focus is convenient and has room for large instruments.

Traditional mirrors are thick to prevent the optical surface from sagging and distorting the image as the telescope is moved around the sky. Large mirrors can weigh many tons and are expensive to make and difficult to support. Also, they cool slowly at nightfall. Expansion and contraction in the cooling mirror causes distortion in the images.

2

Smaller telescopes are often found with a Newtonian focus, the arrangement that Isaac Newton used in his first reflecting telescope. The Newtonian focus is inconvenient for large telescopes as shown at right.

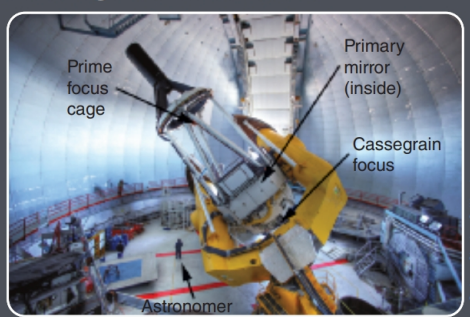




Many small telescopes such as the one at left use a **Schmidt-Cassegrain focus**.

3

Shown below, the Canada-France-Hawaii Telescope can be used at either the prime focus or the Cassegrain focus. Note the human figure at the lower left.

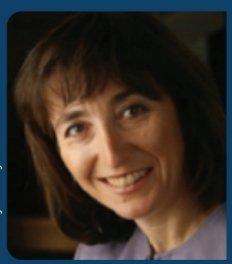


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CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Courtesy Wendy Freedman

Wendy Freedman

Wendy Freedman

In the early 20th century Edwin Hubble discovered the expansion of the universe, measuring distances to Cepheid variable stars (Figure 9.3) in other galaxies and giving the first estimate of the rate of expansion with what is known as the Hubble constant (Figure 10.4). In 1990, the Hubble Space Telescope was launched, aiming to measure more precisely the distances to the galaxies and the rate of expansion. The Hubble Space Telescope Key Project on the Extragalactic Distance Scale was led by Canadian astronomer Wendy Freedman. Freedman was already an accomplished professional. After receiving her Ph.D. from the University of Toronto in 1984, she became the first woman to join the Observatories of the Carnegie Institution for Science in Pasadena, California; 20 years later, she was named a director of the Carnegie Observatories. For her work on the measurement of the Hubble constant, Wendy Freedman was awarded the prestigious 2009 Gruber Cosmology Prize. She has received many honours for her studies of galactic evolution and the evolution of stellar populations, as well as for her leadership in bringing observational cosmology into the 21st century. During her work as co-leader of the Carnegie Supernova Project, research on the galactic distance scale and refinement of the estimate of cosmological expansion led her to identify better indicators of cosmological distances; that is, type Ia supernovae. She is currently chair of the board for the Giant Magellan Telescope Organization, a distinguished international consortium of leading universities and science institutions that is building a 25-m telescope at Carnegie's Las Campanas Observatory in Chile. With unprecedented resolving power—10 times greater than the Hubble Space Telescope—and adaptive optics to battle atmospheric disturbances, this 21st-century telescope will tackle the newest questions in cosmology (Figure 4.10c).

The largest fully steerable radio telescope in the world is at the National Radio Astronomy Observatory in West Virginia, USA. The telescope has a reflecting surface 100 m in diameter made of 2004 computer-controlled panels that adjust to maintain the shape of the reflecting surface. The largest radio dish in the world is 500 m in diameter: FAST (Five-hundred-meter Aperture Spherical radio Telescope) is built into a mountain depression in southwest China. Radio waves are focused on a receiving antenna suspended above the collecting surface (Figure 4.11a).

Arrays of many smaller telescopes combined act as one radio telescope, with the effective area as large as the separation of the most distant dishes. Such an interferometer is capable of high-resolution radio maps of celestial objects. Radio astronomers from 20 countries are now building the Square Kilometre Array (SKA), which will consist of thousands of radio dishes in Australia and South Africa spanning 6000 km. Chajnantor Plateau in Atacama Desert in Chile, 5000 m above sea level, is the site of another international radio interferometer, Atacama Large



JEFF DAI / SCIENCE PHOTO LIBRARY



Andre Renard, Dunlap Institute, University of Toronto



NRAO

Figure 4.11 (a) The Five-hundred-meter Aperture Spherical Telescope (FAST). Portions of the dish can be deformed into a 300-m movable parabolic surface so that the stationary telescope has some ability to track an object in the sky. (b) With unusual design and novel digital technology, Canadian Hydrogen Intensity Mapping Experiment (CHIME) will enable scientists to measure the expansion history of the universe by mapping hydrogen in the early universe. (c) The Event Horizon Telescope (EHT) achieved a resolving power sufficient to photograph the light surrounding supermassive black holes, in a distant galaxy M87 (see Figure 10.22) and at the centre of the Milky Way.

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Millimeter/Submillimeter Array (ALMA). Not all radio telescopes are circular or parabolic dishes. The Canadian Okanagan valley, protected by national regulation against human-made radio-frequency interference, is a site of the Canadian Hydrogen Intensity Mapping Experiment (CHIME) radio telescope. Its four semi-cylinders are not movable; it observes the sky as Earth turns. It works in collaboration with steerable radio telescopes, which follow up on its discovered targets like pulsars and strange radio bursts (Figure 4.11b).

The largest interferometers today operate through a technique called Very Long Baseline Interferometry (VLBI). VLBI uses a worldwide network of radio telescopes over very great distances across the globe. A group of telescopes from all over the world—Chile, Hawaii, Mexico, USA, Spain, the South Pole, Greenland, and France—are linked together into Event Horizon Telescope (EHT), an interferometer with the effective size of the size of our planet (Figure 4.11c).

4.4 Astronomical Instruments and Techniques

Just looking through a telescope doesn't tell you much. To learn about planets, stars, and galaxies, you must be able to analyze the light the telescope gathers. Special instruments attached to the telescope make that possible.

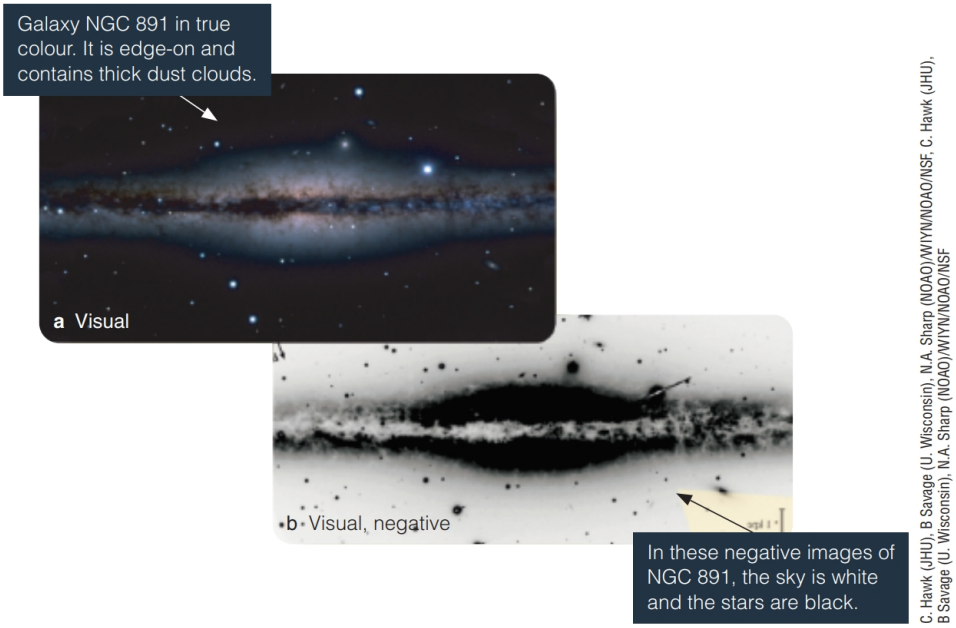
Imaging Systems and Photometers

The photographic plate was the first image-recording device used with telescopes. Brightness of objects imaged on a photographic plate can be measured with a lot of hard work, yielding only moderate precision. Astronomers also build **photometers**, sensitive light meters to measure the brightness of individual objects very precisely. Modern telescopes are equipped with **charge-coupled devices (CCDs)**, which are used as both image-recording devices and photometers. A CCD is a specialized computer chip containing as many as a million or more microscopic light detectors arranged in an array about the size of a postage stamp. These array detectors can be used like a small photographic plate, but they have dramatic advantages over both photometers and photographic plates. CCDs can detect both bright and faint objects in a single exposure and are much more sensitive than a photographic plate. Images are digitized, or converted to numerical data, and can be read directly into a computer memory for later analysis. Although CCDs for astronomy are extremely sensitive and therefore expensive, less sophisticated CCDs are now used in commercial video and digital cameras. Infrared astronomers also use array detectors similar in operation to optical CCDs. At some other wavelengths, photometers are still used for measuring the brightness of celestial objects.

The digital data representing an image from a CCD or other array detector are easy to manipulate to bring out details that would not otherwise be visible. For example, astronomical images are sometimes reproduced as negatives, with the sky white and the stars dark. This makes the faint parts of the image easier to see (Figure 4.12). Astronomers

photometer Sensitive astronomical instrument that measures the brightness of individual objects very precisely.

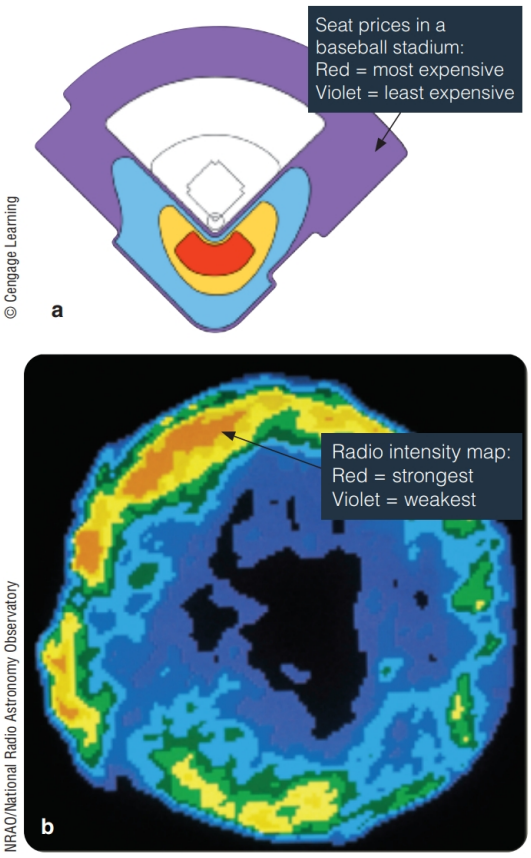
charge-coupled device (CCD) An electronic device consisting of a large array of light-sensitive elements used to record very faint images.



C. Hawk (JHU), B Savage (U. Wisconsin), N.A. Sharp (NOAO)/WIYN/NOAO/NSF. C. Hawk (JHU), B Savage (U. Wisconsin), N.A. Sharp (NOAO)/WIYN/NOAO/NSF

Figure 4.12 (a) Astronomical images can be manipulated to bring out difficult-to-see details. The colour photo of this galaxy is dark, and the dust clouds in the galaxy's central plane do not show very well. (b) The observing team produced this negative image to show the dust clouds more clearly.

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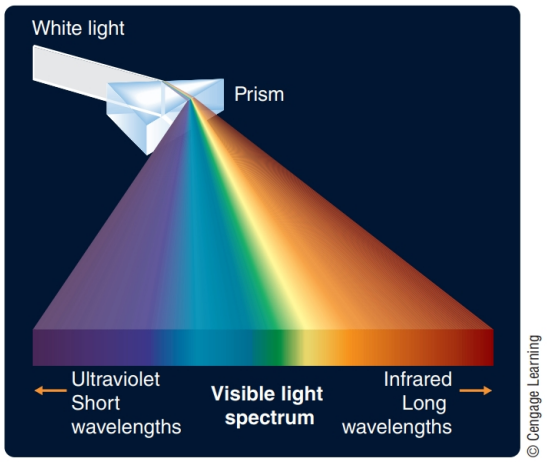
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NRAO/National Radio Astronomy Observatory

Figure 4.13 (a) A contour map of a baseball stadium shows regions of similar admission prices. The most expensive seats are those behind home plate. (b) A false-colour radio map of Tycho's supernova remnant, the expanding shell of gas produced by the explosion of a star in 1572. The radio contour map has been colour-coded to show intensity.

also manipulate images to produce false-colour images in which the colours represent different levels of intensity and are not related to the true colours of the object. For example, because humans can't see radio waves, astronomers must convert them into something perceptible. One way is to measure the strength of the radio signal at various places in the sky and draw a map in which contours mark areas of uniform radio intensity. Compare such a map to Figure 4.13a, a seating diagram for a baseball stadium in which the contours mark areas in which the seats have the same price. Contour maps are very common in radio astronomy and are often reproduced using false colours (Figure 4.13b).

Spectrographs

To analyze light in detail, you need to spread the light out according to wavelength into a spectrum, a task performed by a **spectrograph**. You can understand how this



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Figure 4.14 A prism bends light by an angle that depends on the wavelength of the light. Short wavelengths bend most and long wavelengths least. Thus, white light passing through a prism is spread into a spectrum.

works by reproducing an experiment performed by Isaac Newton in 1666. Boring a hole in his window shutter, Newton admitted a thin beam of sunlight into his darkened bedroom. When he placed a prism in the beam, the sunlight spread into a beautiful spectrum on the far wall. From this and similar experiments, Newton concluded that white light was made of a mixture of all the colours.

Newton didn't think in terms of wavelength, but you can use that modern concept to see that the light passing through the prism is bent at an angle that depends on the wavelength (see Figure 4.14). Violet (short-wavelength) light bends most, and red (long-wavelength) light least. Thus, the white light entering the prism is spread into what is called a **spectrum**. A typical prism spectrograph contains more than one prism to spread the spectrum wider, plus lenses to guide the light into the prism and to focus the light onto a photographic plate. Most modern spectrographs use a grating in place of a prism. A grating is a piece of glass with thousands of microscopic parallel lines scribed onto its surface. Different wavelengths of light pass and bend through the grating at slightly different angles, so white light is spread into a spectrum and can be recorded, often by a CCD camera. Recording the spectrum of a faint star or galaxy can require a long time exposure, so astronomers have developed multiobject spectrographs that can record the spectra

spectrograph A device that separates light by wavelengths to produce a spectrum.

spectrum A range of electromagnetic radiation spread into its component wavelengths (colours)—for example, a rainbow; also the representation of a spectrum as a graph showing intensity of radiation as a function of wavelength or frequency.

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of as many as 100 objects simultaneously. Multiobject spectrographs automated by computers have made large surveys of many thousands of stars or galaxies possible.

Because astronomers understand how light interacts with matter, a spectrum carries a tremendous amount of information, as you will see in more detail in Chapter 5. That makes a spectrograph the astronomer's most powerful instrument. Astronomers are likely to remark, "We don't know anything about an object until we get a spectrum," and that is only a slight exaggeration.

4.5 Airborne and Space Observatories

You have learned about the observations that ground-based telescopes can make through the two atmospheric windows in the visible and radio parts of the electromagnetic spectrum. Most of the rest of the electromagnetic spectrum—infrared, ultraviolet, X-ray, and gamma-ray radiation—never reaches Earth's surface. To observe at these wavelengths, telescopes must fly above the atmosphere in high-flying aircraft, rockets, balloons, and satellites. The only exceptions are observations that can be made in what are called the near-infrared and the near-ultraviolet, almost the same wavelengths as visible light.

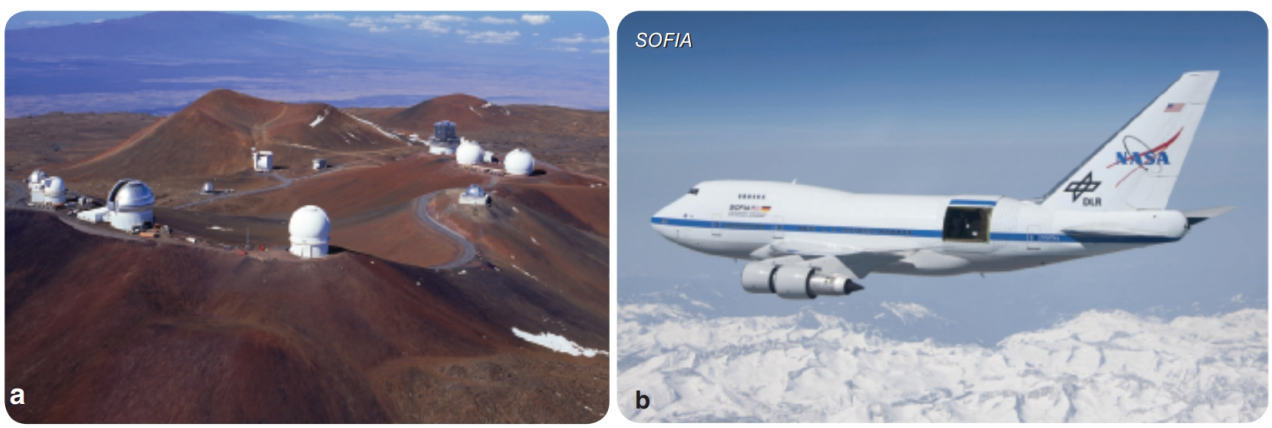
The Ends of the Visual Spectrum

Astronomers can observe from the ground in the near-infrared just beyond the red end of the visible spectrum because some of this radiation leaks through the atmosphere in narrow, partially open, atmospheric windows ranging in wavelength from 1200 nm to about 30 000 nm. Infrared astronomers usually describe wavelengths in micrometres or microns (10^{-6} m), so they refer to this wavelength range as 1.2 to 30 microns. In this range, most of the radiation is absorbed by water vapour and carbon dioxide molecules in Earth's atmosphere, so it is an advantage to place telescopes on the highest mountains where the air is especially thin and dry. For example, a number of important infrared telescopes are located on the summit of Mauna Kea in Hawaii at an altitude of 4200 m (Figure 4.15a). The largest telescope in the world dedicated to near-infrared survey of the sky is European Southern Observatory's VISTA (Visible and Infrared Survey Telescope for Astronomy) at the Paranal Observatory in Chile.

The far-infrared range, which includes wavelengths longer than 30 microns, can tell us about planets, comets, forming stars, and other cool objects, but these wavelengths are absorbed high in the atmosphere. To observe in the far-infrared, telescopes must venture to high altitudes. Remotely operated infrared telescopes suspended under balloons have reached altitudes as high as 41 km.

The Stratospheric Observatory for Infrared Astronomy (SOFIA), a Boeing 747SP aircraft that carries a 2.5-m telescope (Figure 4.15b), can get above more than 99 percent of the water vapour in Earth's atmosphere, allowing observations at infrared wavelengths otherwise accessible only from space telescopes.

At the short-wavelength end of the spectrum, near-ultraviolet, which can't be detected by human eyes, can be



Richard Wainscoat Aina Kai LLC

NASA

Figure 4.15 (a) Optical, infrared, and submillimetre radio telescopes at 4200 m above sea level on Mauna Kea in Hawaii. The high altitude, low atmospheric moisture, lack of nearby large cities, and location near the equator make this mountain one of the best places on Earth to build an observatory. (b) SOFIA, the Stratospheric Observatory for Infrared Astronomy, a joint project of NASA and the German Aerospace Center (DLR), flies at altitudes up to 14 km, where it collects light at infrared wavelengths unobservable even from high mountaintops.

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recorded by CCDs. Wavelengths shorter than about 290 nm—the far-ultraviolet, X-ray, and gamma-ray ranges—are completely absorbed by the ozone layer extending from 20 km to about 40 km above Earth's surface. No mountain is that high, and no balloon or airplane can fly that high, so astronomers cannot observe far-UV, X-ray, and gamma-ray radiation without going into space.

Telescopes in Space

Earth's atmosphere is transparent in two windows, in the visible and radio parts of the electromagnetic spectrum. Most of the rest of the electromagnetic radiation—infrared, ultraviolet, X-ray, and gamma ray—never reaches Earth's surface; it is absorbed high in Earth's atmosphere. To observe at these wavelengths, telescopes must go above the atmosphere.

There is no need to place radio telescope above the atmosphere because radio waves reach ground level. However, linked with Earth-based telescopes, orbiting radio telescopes greatly increase baseline and effective radius of an interferometer. Few Space Very Large Baseline Interferometers (Space VLBI) projects worked over the years. Until recently, Spektr-R (or RadioAstron), an international project led by Russia, had a scientific satellite with a 10-m radio telescope as a part of Space VLBI, making baseline distance equivalent to halfway to the Moon.

The Hubble Space Telescope, named after Edwin Hubble, the astronomer who discovered the expansion of the universe, is the most successful telescope ever to orbit Earth (Figure 4.16a). It was launched in 1990 and contains a 2.4-m mirror plus instruments that can observe at near-infrared, visual, and near-ultraviolet wavelengths. It is controlled from a research centre on Earth and observes continuously. Nevertheless, there is time to complete only a fraction of the projects proposed by astronomers from around the world.

Most observations made by the Hubble Space Telescope are at visual wavelengths, so its greatest advantage in being above Earth's atmosphere is the lack of seeing distortion. For 30 years it has been providing humanity with the deepest views of the universe. Astronomers hope that it will last until it is replaced by the James Webb Space Telescope, planned to launch in 2021 (Figure 4.16b). HST has a 2.4-m mirror. The Webb telescope's primary mirror will have a diameter of 6.6 m.

In 2009, NASA launched the Kepler mission (Figure 4.17a), a space telescope designed to look for Earth-like planets around other stars, specifically for those that could be suitable for harbouring life. The Kepler mission has made outstanding discoveries of thousands of such planets. In 2018, it was replaced by the Transiting Exoplanet Survey Satellite (TESS) (Figure 4.17b), designed to search for exoplanets using the same transit method but in an area 400 times larger than that covered by the Kepler mission.

Most of the emission in far-infrared is thermal, from interstellar dust warmed by absorbed starlight,

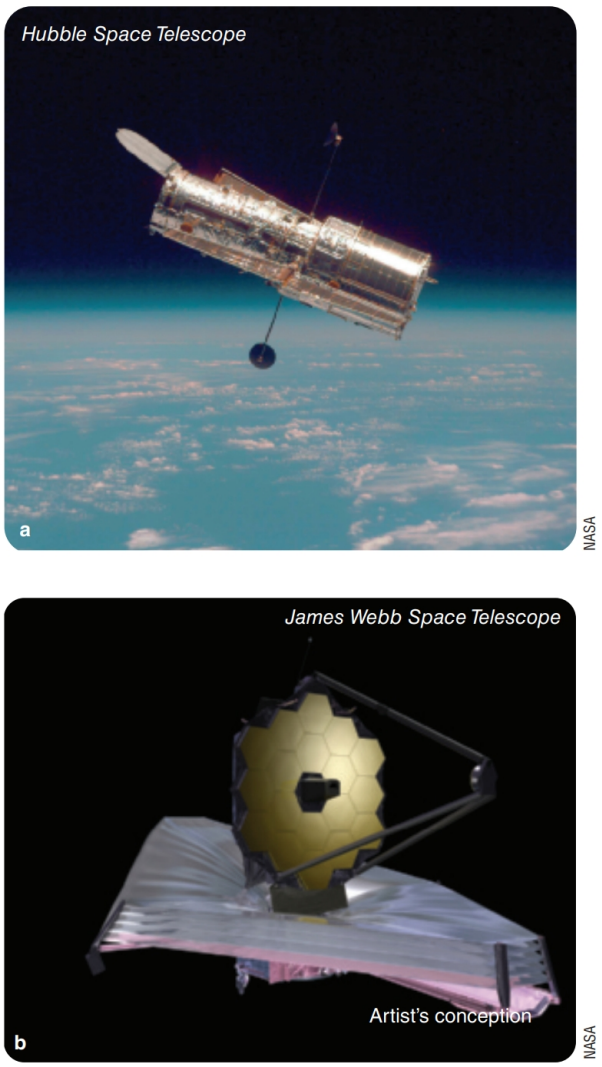
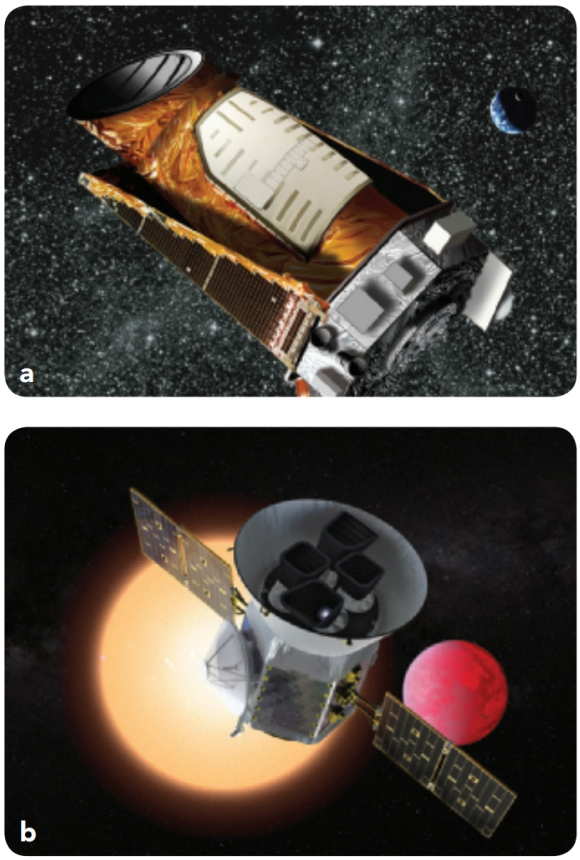


Figure 4.16 (a) The Hubble Space Telescope (HST) orbits Earth at an average of 570 km above the surface. In this image the telescope is viewing toward the upper left. (b) An artist's conception of the eventual successor to HST, the James Webb Space Telescope (JWST), a collaboration among NASA, the European Space Agency (ESA), and the Canadian Space Agency (CSA). JWST will be located in solar orbit 1.5 million km from Earth and will not have an enclosing tube; it will resemble a radio dish more than a conventional optical telescope. It will observe the universe from behind a multilayered sunscreen larger than a tennis court.

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(a) NASA/JPL-Caltech/Wendy Stenzel (b) NASA's Goddard Space Flight Center

Figure 4.17 (a) NASA's *Kepler* satellite detected planets by measuring small changes in the brightness of a star when an orbiting planet transited in front of it. During its more than nine-and-a-half years of service, *Kepler* detected 2662 planets. (b) Illustration of the Transiting Exoplanet Survey Satellite (TESS) in front of a lava planet orbiting its host star. Its array of wide-field cameras can survey 85 percent of the sky. TESS will study the masses, sizes, densities, and orbits of rocky planets in the habitable zones of their host stars.

including star-forming regions embedded in interstellar clouds (Figure 4.18b). Telescopes that observe in the far-infrared must be protected from heat and must get above Earth's absorbing atmosphere. Since heated objects emit infrared radiation, if a telescope becomes warm it will emit infrared radiation many times greater than that emitted by the distant object it is intended to observe—imagine trying to look at a dim, moonlit scene through binoculars that are glowing brightly. Such telescopes have limited lifetimes because they must carry coolant to chill their optics. The most sophisticated of the infrared telescopes put in orbit, the Herschel Space Observatory, was cooled to −269°C. Named after William Herschel, the discoverer of infrared light, the Herschel telescope made important discoveries concerning star and planet formation, distant galaxies, and more before it ended its mission. The older Spitzer Space Telescope (SST), launched in 2003 for a five-year mission, still operates today. SST became the first telescope to directly capture light from exoplanets, the first time extrasolar planets had actually been visually seen. One of its goals was to observe star formation inside gas clouds, which absorb visible light but are seen as transparent in infrared.

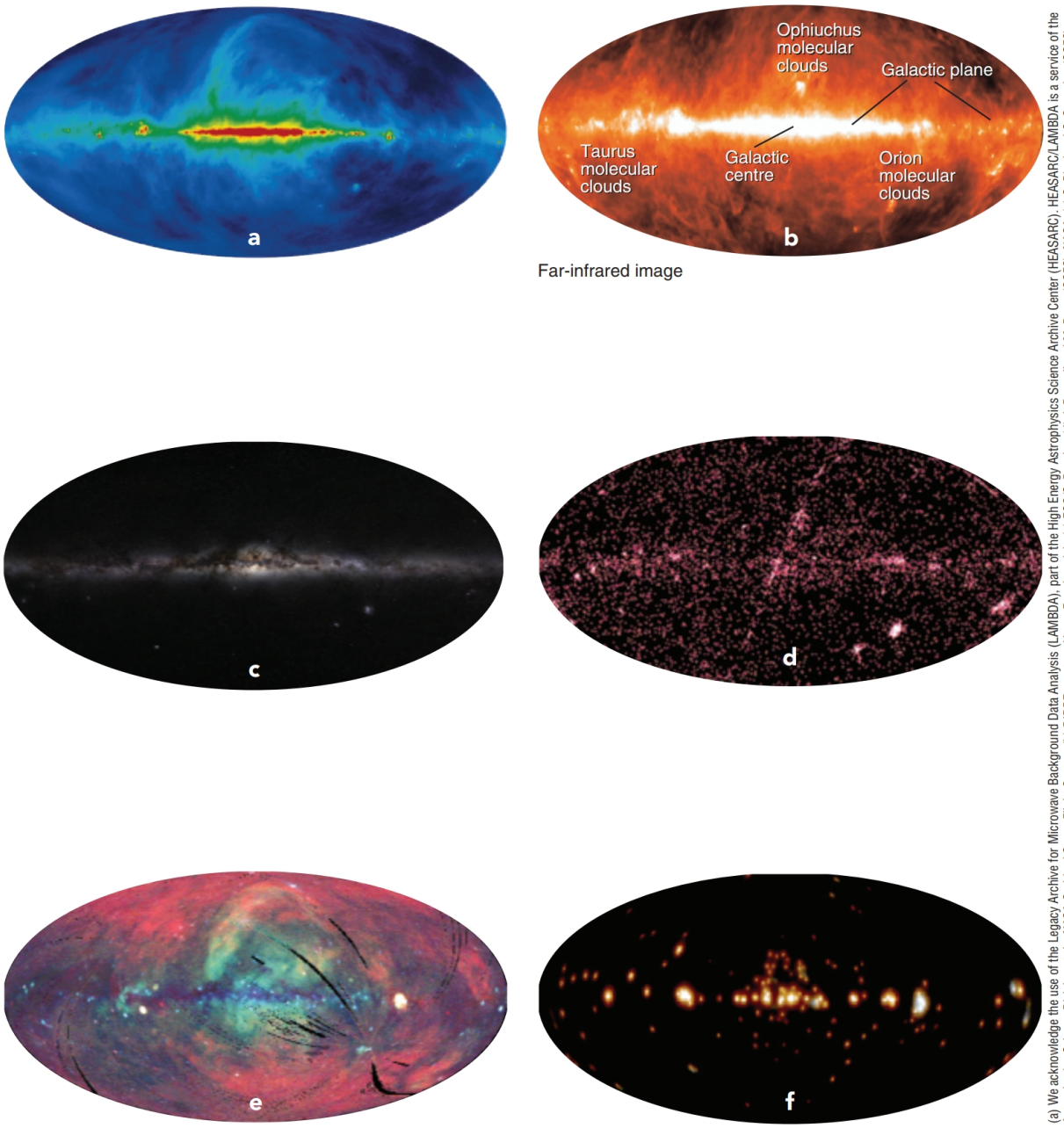
High-energy astrophysics refers to the use of X-ray and gamma-ray observations of the sky. Making such observations is difficult but can reveal the secrets of processes such as the collapse of massive stars, black hole collisions, eruptions of supermassive black holes, and many strange high-energy phenomena that are awaiting explanations (Figures 4.18e and 4.18f).

One of the first gamma-ray observatories was the Compton Gamma Ray Observatory, launched in 1991. It mapped the entire sky at gamma-ray wavelengths (Figure 4.18f). The largest X-ray telescope to date, the Chandra X-ray Observatory, was launched in 1999 into the orbit a third of the way to the Moon. Chandra is named for the late Indian-American Nobel Laureate Subrahmanyan Chandrasekhar, who was a pioneer in many branches of theoretical astronomy. The Chandra telescope has made important discoveries about everything from star formation to monster black holes in distant galaxies. The European INTEGRAL satellite was launched in 2002 and has been very productive in the study of violent eruptions of stars and black holes. International collaboration led by NASA launched in 2008 the Fermi Gamma-ray Space Telescope, named in honour of Enrico Fermi, a pioneer in high-energy physics. It is capable of mapping large areas of the sky to high sensitivity and also observing specific events called gamma-ray bursts.

Astronomy has come to depend on observations that cover the entire electromagnetic spectrum. More orbiting space telescopes are planned that will be more versatile and more sensitive.

Besides electromagnetic spectrum, or light, we can learn about cosmos by analyzing sources of information, such as neutrinos and gravitational waves. You will see about neutrino observatories in Chapter 7, and gravitational waves in Chapter 8.

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(a) We acknowledge the use of the Legacy Archive for Microwave Background Data Analysis (LAMBDA), part of the High Energy Astrophysics Science Archive Center (HEASARC). HEASARC/LAMBDA is a service of the Astrophysics Science Division at the NASA Goddard Space Flight Center.; (b) DIRBE courtesy Henry Freudenreich; (c) ESO/S. Brunier; (d) J. Bonnell and M. Perez (GSFC), NASA; (e) S. Digel and S. Snowden (GSFC), ROSAT Project, MPE, NASA; (f) N. Gehrels, D. Macomb, D. Bertsch, D. Thompson, R. Hartman (GSFC), EGRET, NASA

Figure 4.18 In these images the entire sky as seen from Earth has been projected onto ovals, with the centre of the galaxy at the centre of each oval. The Milky Way extends from left to right. Two nearby galaxies, Magellanic Clouds, are dots on the lower right. (a) Radio: we see a range of frequencies with the different intensity of radio emission colour coded, with red being the strongest and blue being the weakest. As you can see, if you compare this to the optical image below, in our own galaxy the Milky Way is a very strong emitter of radio waves. (b) In the far-infrared image, the dusty disk of our Milky Way is prominent. Clouds and filaments of dust in our galaxy also make intricate patterns pervading most of the sky. (c) In the human-visible image, the gas and dust obscure the view of inner parts of the Milky Way, such as the central bulge. (d) The ultraviolet image shows more energetic sources, which include very hot stars, quasars, external galaxies, supernovae, and nebulae. (e) X-rays are about 1000 times more energetic than visible light. The gas and dust clouds that line the plane of our galaxy absorb X-rays as well as optical light and produce the dark bands running through the galactic centre. (f) Gamma rays have more than a million times the energy of visible light. This image highlights the most intense gamma-ray sources. Some of these have been identified as active galactic nuclei, neutron stars, and quasars. Most, however, remain a mystery and have not yet been identified.

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The **Big Picture**

Telescopes are creations of curiosity. You look through a telescope to see what the unaided eye cannot detect about the universe. The history of astronomy is the history of bigger and better telescopes gathering more and more light to search for fainter and more distant objects to try to satisfy human curiosity. Curiosity is a noble trait—the mark of an active, inquiring mind. At the limits of human curiosity lies the fundamental question, "What are we?" Telescopes extend and amplify our senses, but they also extend and amplify our curiosity about the universe around us. When people find out how something works, they say their curiosity is satisfied. Curiosity is an appetite-like hunger or thirst, but it is an appetite for understanding. And, like hunger, curiosity rises again and again, pushing the boundaries of human knowledge further and further. As astronomy expands our horizons and we learn how distant stars and galaxies work, we feel satisfied because we are learning about ourselves.

Review and **Discussion Questions**

Review Questions

1. Why would you not plot sound waves in the electromagnetic spectrum?
2. The Moon has no atmosphere at all. In what way could astronauts talk on the Moon?
3. If you had limited funds to build a large telescope, which type would you choose: a refractor or a reflector? Why?
4. Why do nocturnal animals usually have large pupils in their eyes? How is that related to the way astronomical telescopes work?
5. Why do optical astronomers often put their telescopes at the tops of mountains, while radio astronomers sometimes put their telescopes in deep valleys?
6. Why do radio telescopes have relatively poor resolving power?
7. The Moon has no atmosphere at all. What advantages would you have if you built an observatory on the lunar surface?
8. Why must telescopes observing at far-infrared wavelengths be cooled to low temperatures?
9. What purpose do the colours in a false-colour image or map serve?
10. Would the advancement in detector sensitivity enable us to receive X-rays and gamma rays from cosmic sources here on Earth's surface and thus eliminate the need for orbiting telescopes?
11. What might you detect with an X-ray telescope that you could not detect with an infrared telescope?
12. Why would radio astronomers build identical radio telescopes in many different places around the world?
13. Why would it be useful to place a radio telescope in orbit even though radio waves come to the surface of Earth?
14. **How Do We Know?** How is the resolution of an astronomical image related to the precision of a measurement?

Discussion Questions

1. Why does the wavelength response of the human eye match the visual window of Earth's atmosphere so well?
2. Most people like beautiful sunsets with brightly glowing clouds, bright moonlit nights, and twinkling stars. Astronomers don't. Why?

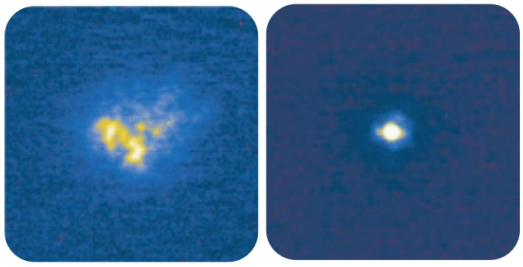
Problems

1. Compare the light-gathering power of one of the 10-m Keck telescopes on Mauna Kea, Hawaii (the two domes on the right in Figure 4.15a) with that of a 0.5-m telescope.
2. How does the resolving power of the 5-m telescope on Mount Palomar near San Diego compare with that of the 2.5-m Hubble Space Telescope? Why does HST generally still outperform the Palomar 5-m telescope?
3. If you build a telescope with a focal length of 1.3 m, what focal length does the eyepiece need to give a magnification of 100 times?

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Learning to Look

1. The two images below show a star before and after an adaptive optics system attached to the telescope was switched on. What causes the distortion in the first image, and how do adaptive optics correct the image?



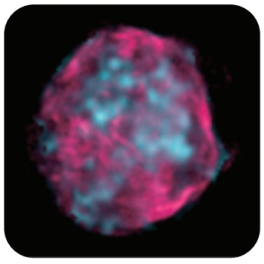
European Southern Observatory

2. The star images in the photo below are tiny disks, but the diameter of these disks is not related to the diameter of the stars. Explain why the telescope can't resolve the diameter of the stars. What does cause the apparent diameters of the stars?



NASA, ESA, and G. Meylan (Ecole Polytechnique Federale de Lausanne)

3. The X-ray image below shows the remains of an exploded star. Explain why images recorded by telescopes in space are often displayed in representational (false) colour rather than in the colours (wavelengths) received by the telescope.



NASA, CXC, PSU, S. Park

STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *Astronomical Telescopes and Instruments: Extending Humanity's Vision.*

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
- Interactive Quizzing
- Animations
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PART TWO

5 The Sun: The Closest Star

CHAPTER OUTLINE

5.1 The Sun: Basic Characteristics
5.2 Properties of Blackbody Radiation
5.3 The Sun's Surface
5.4 Light, Matter, and Motion
5.5 The Sun's Atmosphere
5.6 Solar Activity

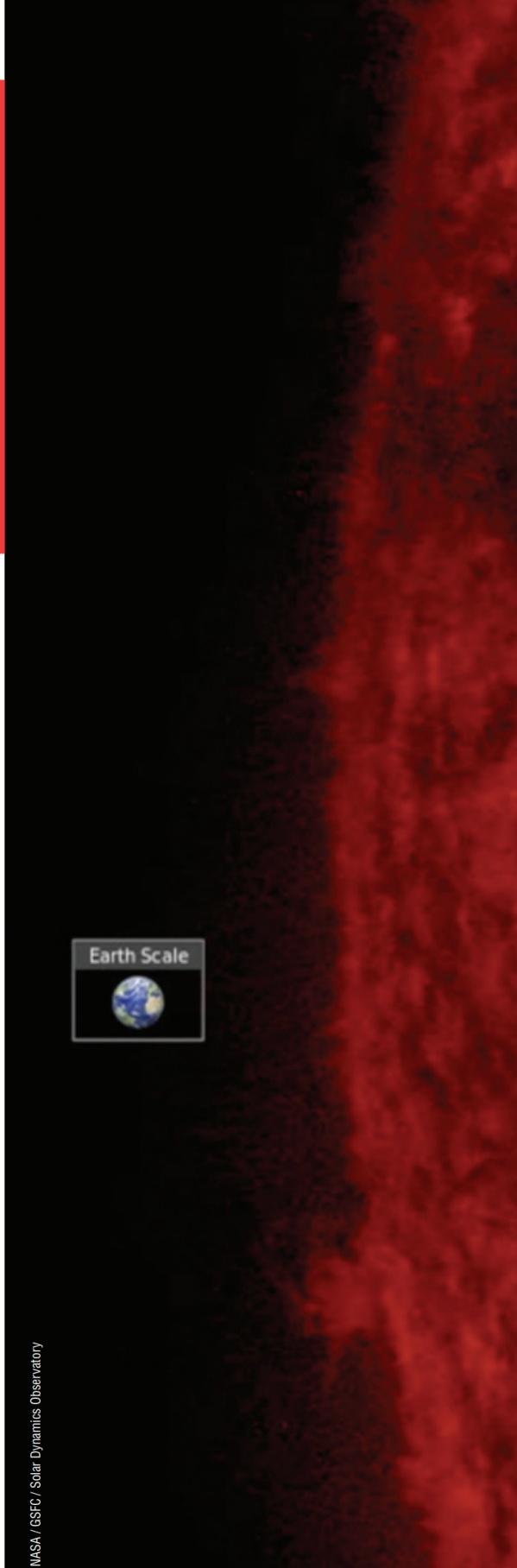
GUIDEPOST

This chapter marks a change in the way you will look at nature. Up to this point, you have been considering what you can see with your eyes alone or aided by telescopes. In this chapter, you will begin to understand how astronomical observations can be linked with physics experiments and theory to unlock celestial secrets that lie beyond what can be seen directly.

The Sun, which is the main source of light and warmth in our solar system, has always been a natural subject of great human curiosity. In this chapter you will discover how careful analysis of sunlight, combined with an understanding of how matter and light interact, paints a detailed picture of the Sun's properties. Here you will find answers to four important questions:

- How do atoms and light interact?
- What can you learn from spectra of celestial objects?
- What can you learn about the Sun by observing its surface and atmosphere?
- Why does the Sun go through cycles of activity?

Although this chapter considers only the star at the centre of our solar system, understanding how astronomers study the Sun leads you onward and outward among the planets, stars, and galaxies that fill the universe, often using the rich information derived from their spectra.



NASA / GSFC / Solar Dynamics Observatory

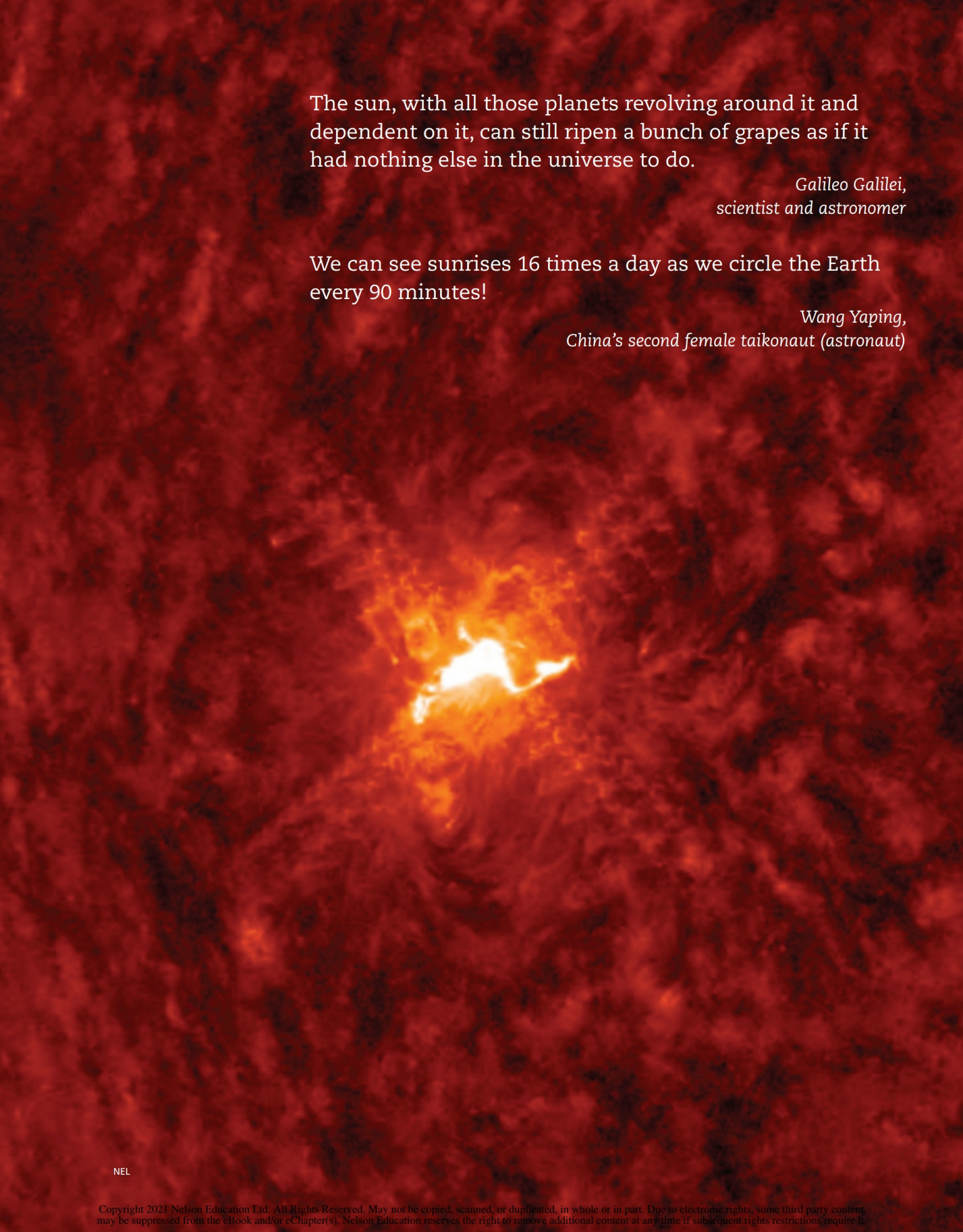
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The sun, with all those planets revolving around it and dependent on it, can still ripen a bunch of grapes as if it had nothing else in the universe to do.

Galileo Galilei,
scientist and astronomer

We can see sunrises 16 times a day as we circle the Earth every 90 minutes!

Wang Yaping,
China's second female taikonaut (astronaut)



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5.1 The Sun: Basic Characteristics

Earthbound humans knew almost nothing about the Sun until the early 19th century, when the German optician Joseph von Fraunhofer studied the rainbow spectrum of sunlight and found that it is interrupted by some 600 dark lines, representing colours that are missing from the sunlight Earth receives. As scientists realized that these **spectral lines** were related to the presence of various types of atoms in the Sun's atmosphere, a window finally opened to real understanding of the Sun's nature. In this chapter, you will look through that window by considering the properties of sunlight and how atoms interact with light to make spectral lines. Once you understand that, you will know how astronomers have determined the chemical composition of the Sun, measured motions of gas on the Sun's surface and in its atmosphere, and detected magnetic fields that drive the Sun's cycle of activity.

An important reason to study the Sun is that life on Earth depends critically on the Sun. Very small changes in the Sun's luminosity can alter Earth's climate, and a larger change might make Earth uninhabitable. Nearly all of Earth's energy comes from the Sun—the energy in oil, gasoline, coal, and even wood is merely stored sunlight. Furthermore, the Sun's atmosphere of very thin gas extends beyond Earth's position, and changes in that atmosphere, such as eruptions or magnetic storms, can have a direct effect on Earth.

In its general properties, the Sun is very simple. It is a great ball of hot gas held together by its own gravity. Deep inside the Sun's core, energy is produced by nuclear fusion, which is released in the form of radiation and heat. You will explore nuclear fusion in the Sun and other stars in more detail in Chapter 7. The tremendously hot gas inside the Sun has such a high outward pressure that it would explode were it not for its own confining gravity. The Sun's gravity would make it collapse into a small, dense body were it not so hot inside. Like a soap bubble, the Sun is a simple structure balanced between opposing forces that, if unbalanced, would destroy it. This balancing act is also true for other stars, so the Sun gives us insight into the rest of the stars in the universe.

spectral line A bright or dark line in a spectrum at a specific wavelength produced by the absorption or emission of light by certain atoms.

transits of Venus Rare occasions in the orbit of Venus when it passes between Earth and the Sun and can be seen as a tiny dot directly between Earth and the Sun.

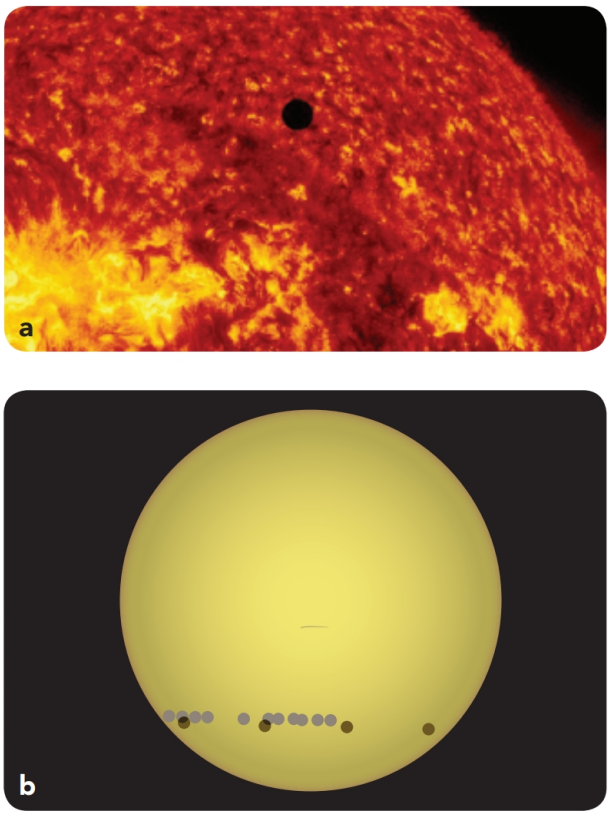
Distance and Size

When you watch the Sun set in the west, you see a glowing disk that is 150 million kilometres from Earth and has a diameter 109 times that of Earth. How do you know this? Recall from Chapter 3 that in the 17th century Johannes Kepler had observed the orbits of the planets and formulated three laws of planetary motion. From Kepler's third law, the relative sizes of the orbits of the planets were already known in astronomical units—one AU being the average distance of the Sun from Earth. For example, the distance of Venus from the Sun was known to be about 0.7 AU. However the magnitude of one AU—the Earth–Sun distance in kilometres—was not known. This problem was ingeniously solved using the parallax effect. Recall from Chapter 3 that the true distance of a nearby object can be calculated from the size of the apparent shift in its position relative to the background as seen from two viewing positions (refer to **Visualizing Astronomy 3.1, The Ancient Universe**). That shift is called parallax. (Refer to **Parallax and Distance** in the Math Reference Cards.)

If you and another astronomer on the opposite side of Earth agree to observe the position of a planet such as Venus at the same moment relative to more distant objects, you could measure that planet's parallax shift due to you and your colleague's different observing locations. Then the distance to Venus in kilometres can be calculated with some trigonometry. From Kepler's third law, knowing that this distance in kilometres is equal to 0.3 AU, you can calculate the value of 1 AU in kilometres, which gives you the distance from Earth to the Sun. From the 17th century onward, astronomers made more and more accurate measurements of this type, especially on rare occasions called **transits of Venus**, when that planet can be seen as a tiny dot directly between Earth and the Sun, as shown in Figure 5.1, so the edge of the Sun's disk acts as a convenient position marker. The distance from Earth to the Sun, combined with the Sun's easily measured angular size, gives you the Sun's diameter.

Johannes Kepler was the first to predict a transit of Venus in 1631. Sadly he passed away in 1630 without being able to confirm his prediction. It was not until 1639 that a transit of Venus was observed on Earth by two British astronomers, Jeremiah Horock and William Crabtree. In 1716, Edmund Halley (who is famous for the comet named after him) first proposed using the transit of Venus and the parallax method to try to calculate the Earth–Sun distance. But he too unfortunately died in 1742 before the next transit in 1761. By then, many teams of international researchers around the world worked together to make the necessary observations, in one of the first real international astronomy initiatives. By the next transit in 1769, scientists were able to calculate the distance from Earth to the Sun to within 3 percent of the currently known value. This grand global

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NASA/SDO, AIA; Astronomy Group—Sønderborg and Learmonth Solar Observatory/ESO/Adapted from the GONG project and Arntsgymnasiet i Sønderborg

Figure 5.1 (a) A breathtaking high-resolution image of the 2012 transit of Venus (b) Comparison of Venus's path across the solar disk as observed from Australia (upper track) and Denmark (lower track). Measurement of the small parallax shift allows the distance to Venus to be calculated based on the known distance between the two observatories. Kepler's third law can then be used to find the distance to the Sun.

effort opened the doors to our modern understanding of the true scales of the universe.

Mass and Density

Once you know the distance to the Sun, Newton's laws (Chapter 3) tell you what the Sun's mass needs to be to produce the necessary amount of gravitational force to keep Earth and the other planets in their orbits at their observed speeds. If you know the mass and diameter of the Sun, you can make an easy calculation of the Sun's **density** (mass per volume). Refer to the **Celestial Profiles** in Appendix C, and notice the Sun's mass, equivalent to 333 000 times the mass of Earth, and its average density, only a little bit denser than water. Although the Sun is very large and very massive, the low density and high temperature together tell you that it must be gas from its surface to its centre. When you look at the Sun you see only the outer layers—the surface and atmosphere—of this vast sphere of gas.

In the following sections of this chapter you will learn how, using the results of laboratory physics experiments on Earth, you can know facts as seemingly unknowable as the temperature and composition of the Sun: an object that has never been visited or touched by humans.

5.2 Properties of Blackbody Radiation

You probably have noticed that your toaster's coils glow different colours as they heat up. If they are not too hot, the coils are deep red, but as they heat up they grow brighter and yellower. Yellow-hot is hotter than red-hot, but not as hot as white-hot. Different parts of the Sun's surface also glow slightly different colours depending on their temperatures. To understand the Sun's temperature, you must understand the structure and behaviour of the atoms that make up the Sun.

Atoms and Subatomic Particles

As you know, an **atom** has a massive, compact **nucleus** containing positively charged **protons**, usually accompanied by electrically neutral **neutrons**. The nucleus is embedded in a large cloud of relatively low-mass, negatively charged **electrons**. These particles can also exist and move about unattached to an atom.

Charged particles, both protons and electrons, are surrounded by electric fields that they produce. An electric field is a region of space in which another charged particle feels an electric force. Whenever you change the motion of a charged particle, the change in its electric field spreads outward at the speed of light as electromagnetic radiation. If you run a comb through your hair, you disturb electrons in both hair and comb, producing electric sparks and electromagnetic radiation, which you can

density Mass per volume.

atom The smallest unit of a chemical element, consisting of a nucleus containing protons and neutrons and a surrounding cloud of electrons.

nucleus The central core of an atom containing protons and neutrons that carries a net positive charge.

proton A positively charged atomic particle contained in the nucleus of an atom. The nucleus of a hydrogen atom consists of a single proton.

neutron An atomic particle contained in the nucleus, with no charge and about the same mass as a proton.

electron Low-mass atomic particle carrying a negative charge.

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sometimes hear as snaps and crackles if you are standing near a radio.

The Sun is hot, and there are plenty of electrons zipping around, colliding, changing directions and speeds, and thereby making electromagnetic radiation. Protons can also make electromagnetic radiation, but because electrons are less massive, usually it is electrons that do most of the moving around.

molecule Two or more atoms bonded together.

heat Total energy stored in a material as agitation among its particles.

temperature A measure of the average agitation among the atoms and molecules of a material.

Kelvin temperature scale A temperature scale starting at absolute zero (−273°C). A one Kelvin change equals a one degree Celsius change.

absolute zero The theoretical lowest possible temperature at which a material contains no extractable heat energy. Zero on the Kelvin temperature scale.

blackbody radiation Radiation emitted by a hypothetical perfect radiator. The spectrum is continuous, and the wavelength of maximum emission depends on the blackbody's temperature.

wavelength of maximum intensity The wavelength at which a perfect radiator emits the maximum amount of energy; it depends only on the object's temperature.

Wien's law A law stating that the hotter a glowing object is, the shorter will be its wavelength of maximum intensity, inversely proportional to its temperature.

Stefan–Boltzmann law A law stating that hotter objects emit more energy than cooler objects of the same size, in proportion to the fourth power of temperature.

Temperature, Heat, and Blackbody Radiation

The particles inside any object—for example, atoms linked together to form **molecules**, individual atoms, or electrons inside atoms or wandering loose—are in constant motion, and in a hot object they are more agitated than in a cool object. The total agitation of particles in an object is known as *thermal energy*. When you touch a hot object, you feel **heat** as that thermal energy flows into your fingers. **Temperature** is a measure of the average speed of the agitated particles, the intensity of the particle motion.

Astronomers and physicists express temperatures of the Sun and other objects on the **Kelvin temperature scale**. Zero degrees Kelvin (written 0 K) is **absolute zero** (−273°C), the temperature at which an object contains no thermal energy that can be extracted. Water freezes at 273 K and boils at 373 K. The temperature of outer space is about 2.7 K. The Kelvin temperature scale is useful in astronomy because it is based on absolute zero and, consequently, is related directly to the motion of the particles in an object.

Now you can understand why a hot object glows. The hotter an object is, the higher is its thermal energy—the more motion there is among its particles. The agitated particles, including electrons, collide with each other, and when electrons are accelerated, part of the energy is carried away as electromagnetic radiation. The radiation emitted by an opaque object is called **blackbody radiation**, a name translated from a German term that refers to the way a perfect emitter and absorber of radiation would behave. At room temperature, such a perfect absorber would look black, but at higher temperatures it would visibly glow. In astronomy you will find the term *blackbody* actually refers to glowing objects.

Blackbody radiation is quite common. In fact, it is the type of light emitted by an ordinary incandescent light bulb. Electricity flowing through the filament of the bulb heats it to a high temperature, and it glows. You can also recognize the light emitted by a toaster coil as blackbody radiation. Many objects in the sky, including the Sun, primarily emit blackbody radiation because they are mostly opaque.

Two simple laws describe how blackbody radiation works. A hot object radiates at all wavelengths, but there is a **wavelength of maximum intensity** at which it radiates the most energy. **Wien's law** says that the hotter an object is, the shorter is the wavelength of its maximum intensity. This makes sense because in a hotter object, the particles travel faster, collide more violently, and emit more energetic photons, which have shorter wavelengths. This means that hot objects tend to emit radiation at shorter wavelengths and look bluer than cooler objects. Hot stars look bluer than cool stars.

The **Stefan–Boltzmann law** says that hotter objects emit more energy than cooler objects of the same size. That makes sense, too, because the hotter an object is, the more rapidly its particles move and the more violent and more frequent are the collisions that emit energy as photons. In fact, very small changes in temperature lead to very large changes in the total energy emitted. In later sections, you will use these two laws to understand stars and other objects. For more information about the two laws governing blackbody radiation refer to the Math Reference Card on **Blackbody Radiation**.

Figure 5.2 shows plots of the intensity of radiation versus wavelength for three objects with different temperatures, illustrating both Wien's law and the Stefan–Boltzmann law. You can see how temperature determines the colour of a glowing blackbody. The hotter object has its peak intensity at shorter wavelengths, so it emits more blue light than red and thus looks blue. The cooler object emits more red than blue light and consequently looks red. Also, the total area under each curve is proportional

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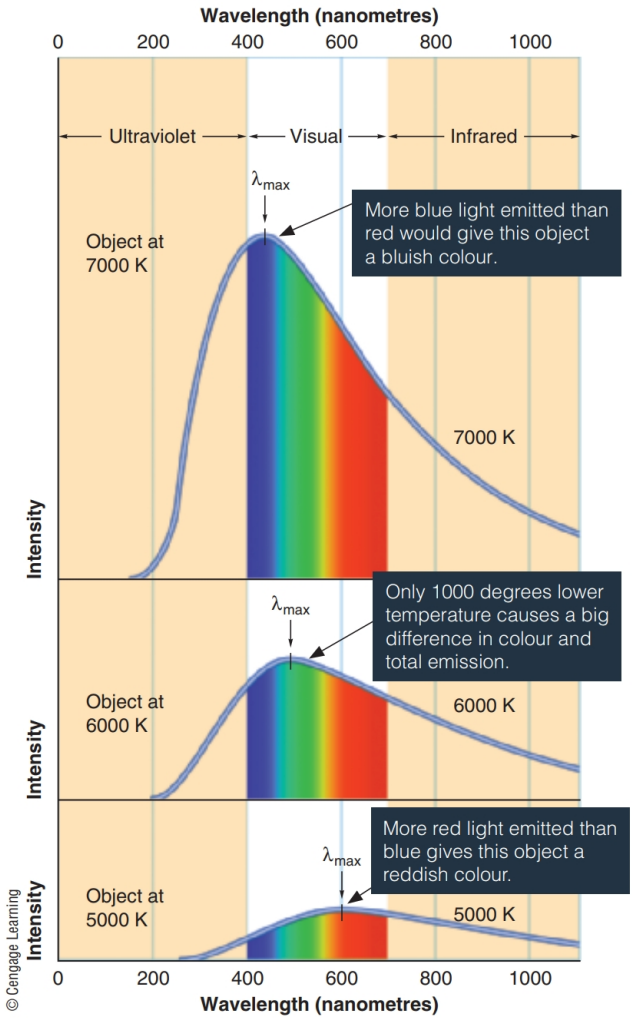


Figure 5.2 These graphs of blackbody radiation from three objects at different temperatures demonstrate that a hot object radiates more total energy (Stefan–Boltzmann law) and that the wavelength of maximum intensity is shorter for hotter objects (Wien's law). The hotter object here will look blue to your eyes, while the cooler object will look red.

to the total energy emitted, so you can see that the hotter object emits more total energy than the cooler object.

Now you can understand why two famous stars, Betelgeuse and Rigel, have such different colours. According to Wien's law, Betelgeuse is cooler than the Sun so it looks red, but Rigel is hotter than the Sun and looks blue. A star with the same temperature as the Sun will appear yellowish. Actually, the peak intensity of light from the Sun is for wavelengths corresponding to green light, but we see the Sun as yellowish because of the way our eyes detect the light. According to the Stefan–Boltzmann law, Rigel also produces more energy from each square metre of its photosphere than does the Sun, which in turn produces more energy from each square metre than does Betelgeuse.

Notice that cool objects may emit little visible radiation but are still producing blackbody radiation. For example, the human body has a temperature of 310 K and emits blackbody radiation mostly in the infrared part of the spectrum. Infrared security cameras can detect burglars by the radiation they emit, and mosquitoes can track you down in total darkness by homing in on your infrared radiation. You have a wavelength of maximum intensity in the infrared part of the spectrum. At your temperature you almost never emit photons with other than infrared wavelengths.

5.3 The Sun's Surface

The Sun's disk looks like a mostly smooth layer of gas (Figure 5.3). Although the Sun seems to have a real surface, it is not solid. In fact, the Sun is gaseous from its outer atmosphere right down to its centre.

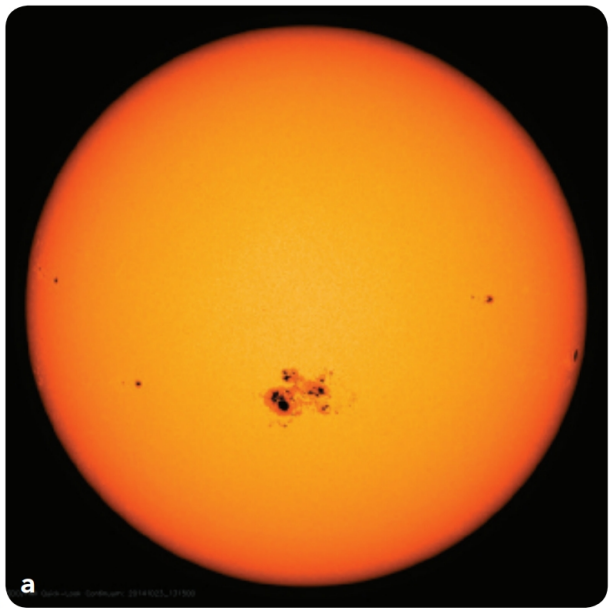
The Photosphere

The visible surface of the Sun is called the **photosphere**. The photosphere is the layer in the Sun's atmosphere that is dense enough to emit plenty of light but not so dense that the light can't escape; the photosphere is the source of most of the sunlight received by Earth. The photosphere is less than 500 km deep. If we built a scale model of the Sun using a bowling ball, the photosphere would be no thicker than a layer of tissue paper wrapped around the ball. If you measure the amount of light of each wavelength coming from the photosphere, plot a curve as shown in Figure 5.2, and then use Wien's law, you will find that the average temperature of the photosphere is about 5800 K.

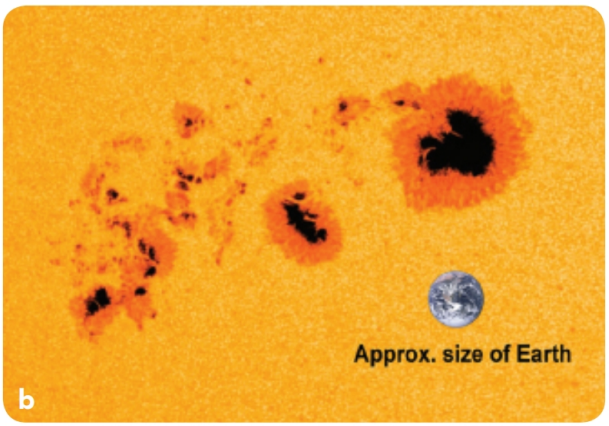
Although the photosphere appears to be substantial, it is really a very low-density gas, 3000 times less dense than the air you breathe. To find gases in the Sun as dense as the air at Earth's surface, you would have to descend about 70 000 km below the photosphere, roughly 10 percent of the way to the Sun's centre. If you could somehow create fantastically efficient insulation, you could fly a spaceship right through the photosphere. The photosphere represents the depth where somebody outside the Sun would no longer be able to see the descending spaceship; conversely, onboard

photosphere The bright visible surface of the Sun.

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NASA



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Figure 5.3 (a) The surface of the Sun (photosphere) as seen through a telescope looks smooth with small dark cooler regions called sunspots (b) Sunspots can be quite large relative to the size of Earth.

the ship, you would no longer be able to see the rest of the universe.

There are regions of the photosphere that appear darker than the rest. These are called **sunspots**. They produce less light than equal-sized pieces of the normal photosphere, and their colour is redder than the average, so from both the Wien and Stefan–Boltzmann laws you can conclude that sunspots are cooler than the photosphere. In fact, they are usually about 1000 to 1500 K cooler. Later in this chapter you will learn about the causes of sunspots and other solar dermatology problems.

Heat Flow in the Sun

At the temperature of 5800 K, every square millimetre of the Sun's photosphere must be radiating more energy than a 60-watt light bulb. This tells you that energy in the form of heat must be flowing outward from the Sun's interior. With all that energy radiating into space, the Sun's surface would cool rapidly if energy did not flow up from inside to keep the surface hot. As you learn more about the surface and atmosphere of the Sun, you will find many phenomena that are driven by this energy flow. Like a pot of boiling soup on a hot stove, the Sun is in constant activity as the heat comes up from below. In high-resolution photographs, the photosphere has a mottled appearance because it is made up of dark-edged regions called granules, and the visual pattern is called **granulation**, which you can see in Figure 5.4a. Each granule is about the size of Alberta and lasts for only 10 to 20 minutes before fading away. Faded granules are continuously replaced by new ones. The colour and amount of light from different portions of the granules show, by both Wien's law and the Stefan–Boltzmann law, that the centres of granules are a few hundred degrees hotter than their edges.

sunspot Relatively cooler, dark spot on the Sun that contains intense magnetic fields.

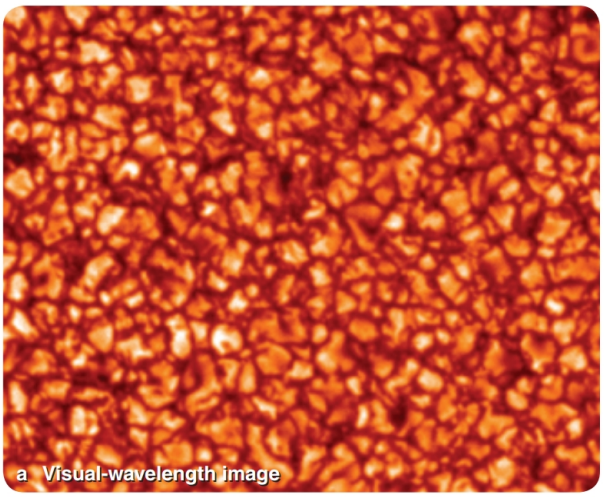
granulation The fine structure of bright regions (grains) with dark edges covering the Sun's surface.

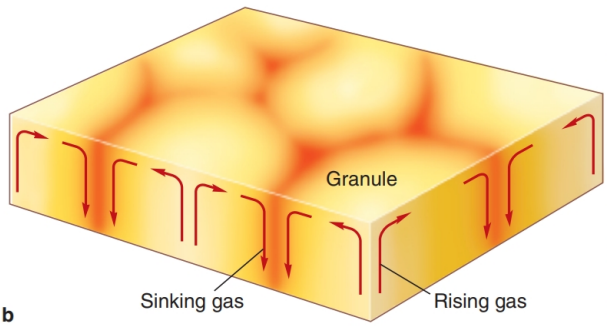
convection Circulation in a fluid driven by heat. Hot material rises and cool material sinks.

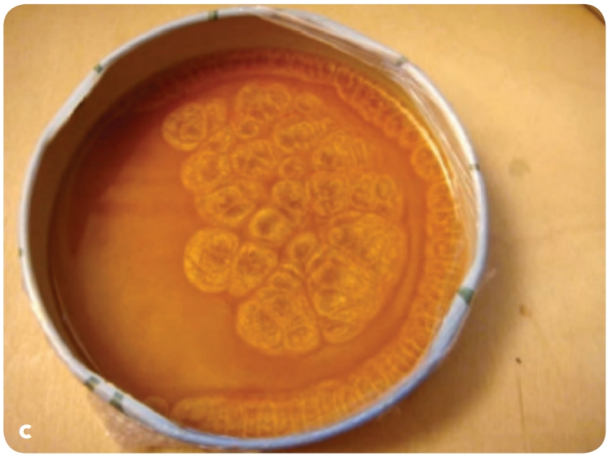
Astronomers recognize granulation as the surface effects of rising and falling currents of gas in and just below the photosphere (the Doppler effect that allows astronomers to measure speeds of these gas currents is discussed later in this chapter). The centres of granules are rising columns of hot gas, and the edges of the granules are cooler, sinking gas. The presence of granulation is clear evidence that energy is circulating through the photosphere by a process known as **convection**, which is demonstrated in Figure 5.4b.

Convection occurs when hot fluid rises and cool fluid sinks, as when, for example, a convection current of hot gas rises above a candle flame. You can watch liquid convection by adding a bit of cool non-dairy creamer to an unstirred cup of hot coffee. The cool creamer sinks, warms, expands, rises, cools, contracts, sinks again, and so on, creating small regions on the surface of the coffee that mark the tops of convection currents. Viewed from above, these regions look much like solar granules.

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Figure 5.4 (a) This ultra-high-resolution image of the photosphere shows granulation. The largest granules here are about the size of Alberta. (b) The granules are tops of rising convection currents just below the photosphere. Heat flows upward as rising currents of hot gas and downward as sinking currents of cool gas. The rising currents heat the solar surface in small regions seen from Earth as granules. (c) Convection cells that form in hot liquid like coffee.

5.4 Light, Matter, and Motion

If light did not interact with matter, you would not be able to see these words. In fact, you would not exist, because, among other problems, photosynthesis would be impossible, and there would be no grass, wheat, bread, rice, or any other kind of food. The interaction of light and matter makes all life possible, and it also makes it possible for you to understand the universe.

Electron Shells

Your study of light and matter begins here with a study of electrons that are within atoms. As you learned in the previous section, electrons and other charged particles produce light when they change speed or direction of their motion. The electrons are bound to the atom by the attraction between their negative charge and the positive charge of the nucleus. This attraction is known as the **Coulomb force**, after the French physicist Charles-Augustin de Coulomb (1736–1806). A positive **ion** is an atom with missing electrons, meaning fewer electrons than protons. For an atom to go through the **ionization** process, there needs to be a certain amount of energy to pull an electron completely away from the attraction of the nucleus. This energy is the electron's **binding energy**, the energy that binds it to the nucleus.

The size of an electron's orbit is related to the energy that binds it to the atom. If an electron orbits close to the nucleus it is tightly bound, and a large amount of energy is needed to pull it away. Consequently, its binding energy is large. An electron orbiting farther from the nucleus is held more loosely, and less energy is needed to pull it away. That means it has less binding energy.

Nature permits atoms only certain amounts (quanta) of binding energy, and the laws that describe how atoms behave are called the laws of **quantum mechanics**. Much of this discussion of atoms is based on the laws of quantum mechanics.

Because atoms can have only certain amounts of binding energy, your model atom can have orbits of only

Coulomb force The electrostatic force of repulsion between like charges or attraction between opposite charges.

ion An atom that has lost or gained one or more electrons.

ionization The process in which atoms lose or gain electrons.

binding energy The energy needed to pull an electron away from its atom.

quantum mechanics The study of the behaviour of atoms and atomic particles.

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certain sizes, called **permitted orbits**. These are like steps in a staircase: You can stand on the number-one step or the number-two step but not on the number-one-and-one-quarter step. The electron can occupy any permitted orbit, but not orbits in between.

The arrangement of permitted orbits depends primarily on the charge of the nucleus, which in turn depends on the number of protons. The number of protons in the nucleus is unique to each element. Consequently, as shown in the diagrams of hydrogen, helium, and boron in Figure 5.5, each kind of element has its own pattern of permitted orbits. Ionized forms of an element have orbital patterns quite different from their un-ionized forms. The arrangement of permitted orbits differs for every kind of atom and ion. **Isotopes** are versions of a given element with different numbers of neutrons. Isotopes of an element have almost—but not quite—the same pattern of permitted electron orbits as each other because they have the same number of electrons but their nuclei have slightly different masses.

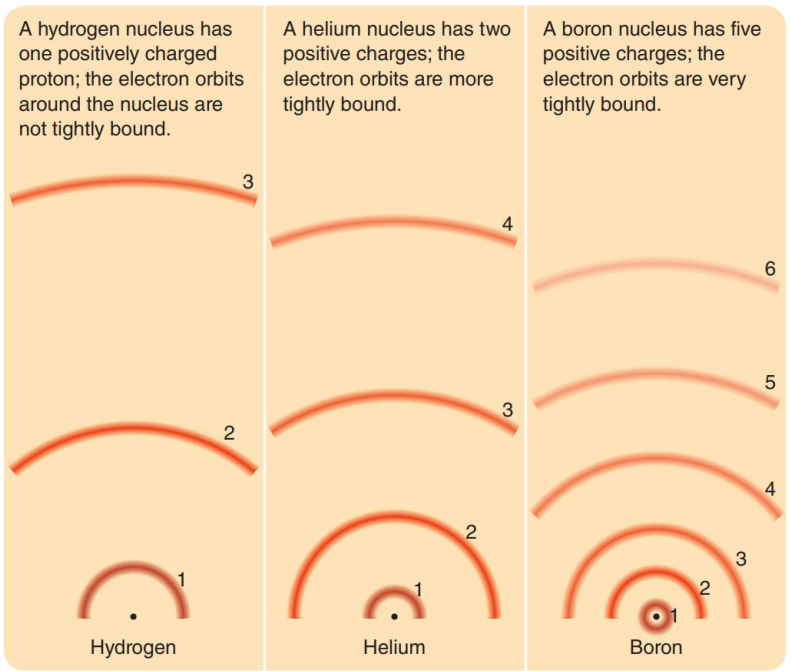


Figure 5.5 The electron in an atom may occupy only certain permitted orbits. Because different elements have different numbers of positively charged protons in their nuclei, the elements have different, unique patterns of permitted orbits. Figure shows only the innermost orbits, with the nucleus shown as a dot.

Excitation of Atoms

Each orbit in an atom represents a specific amount of binding energy, so physicists commonly refer to the orbits as **energy levels**. Using this terminology, you can say that an electron in its smallest and most tightly bound orbit is in its lowest permitted energy level. You could move the electron from one energy level to another by supplying enough energy to make up the difference between the two energy levels. It would be like moving a book from a low shelf to a high shelf: The greater the distance between the shelves, the more energy you would need to raise the book. The amount of energy needed to move the electron is the energy difference between the two energy levels.

permitted orbit One of the unique orbits that an electron may occupy in an atom.

isotopes Atoms that have the same number of protons but a different number of neutrons.

energy level One of the rungs of the ladder of allowed energy states an electron may occupy in an atom.

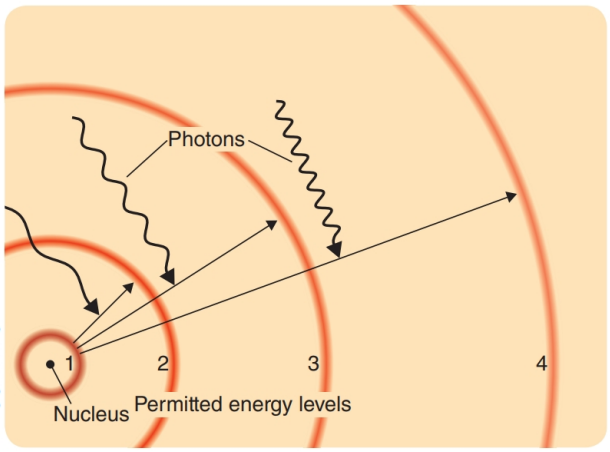
excited atom An atom in which an electron has moved from a lower to a higher energy level.

If you move the electron from a low energy level to a higher energy level, you can call the atom an **excited atom**. That is, you have added energy to the atom by moving its electron. If the electron falls back to the lower energy level, that energy is released. An atom can become excited by collision. If two atoms collide, one or both may have electrons knocked into higher energy levels. This happens very commonly in hot gas, where the atoms move rapidly and collide often.

Another way an atom can get the energy that moves an electron to a higher energy level is to absorb a photon (packet) of electromagnetic radiation (light). Only a photon with exactly the right amount of energy corresponding to the energy difference between two levels can move the electron from one level to another. If the photon has too much or too little energy, the atom cannot absorb it, and the photon passes right by. Because the energy of a photon depends on its wavelength, only photons of certain wavelengths (certain colours) can be absorbed by a given kind of atom. The wavelength of a photon is inversely proportional to its energy. Thus, a photon with higher energy has a shorter wavelength than a photon with lower energy. (Refer to **Wave Properties** in the Math Reference Cards.)

Figure 5.6 shows the lowest four energy levels of the hydrogen atom along with three photons the atom could absorb. The longest-wavelength (reddest) photon has only enough energy to excite the electron from the first to the second energy level, but the shorter-wavelength

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Figure 5.6 Quantum leaps to different permitted orbits (energy levels) due to absorption of photons of differing wavelengths.

(higher-energy, bluer) photons can excite the electron to higher levels. A photon with too much or too little energy cannot be absorbed. Because the hydrogen atom has many more energy levels than shown in Figure 5.6, it can absorb photons of many different wavelengths.

Atoms, like humans, cannot exist in an excited state forever. The excited atom is unstable and must eventually (usually within a billionth to a millionth of a second) give up the energy it has absorbed and return its electron to a lower energy level. The lowest energy level an electron can occupy is called the **ground state**.

When the electron drops from a higher to a lower energy level, it moves from a loosely bound level to one more tightly bound. The atom then has a surplus of energy—the energy difference between the levels—that it can emit as a photon. Study the sequence of events in Figure 5.7 to see how an atom can absorb and emit photons. Jumps of electrons from one orbit to another are sometimes called **quantum leaps**. In popular expression that term has come to mean a huge change, but now you see that it represents a very small change indeed. The quantum leap represents a change of electron motion, so electromagnetic radiation is either released or absorbed in the process.

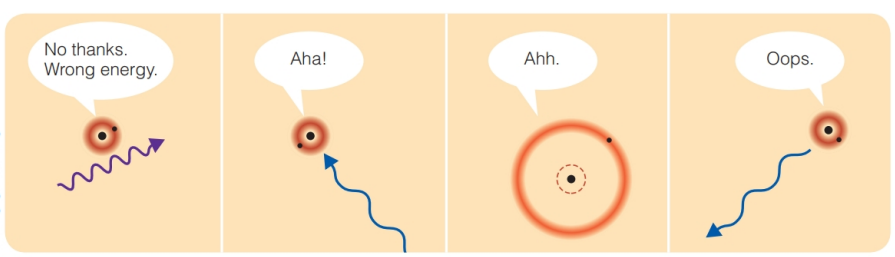
Because each type of atom or ion has its unique set of energy levels, each type absorbs and emits photons with a unique set of wavelengths. As a result, you can identify the elements in a gas by studying the characteristic wavelengths (spectral lines) of light absorbed or emitted. It is important to note that the wavelengths (colours) emitted and absorbed by leaping electrons are determined not by the starting or ending energy level of the jump but by the difference between the levels (see **Visualizing Astronomy 5.1, Atomic Spectra**, later in this chapter).

The process of excitation and emission is a common sight in urban areas at night. A neon sign glows when atoms of neon gas in the glass tube are excited by electricity flowing through the tube. As the electrons in the electric current flow through the gas, they collide with the neon atoms and excite them. And immediately after an atom is excited, its electron drops back to a lower energy level, emitting the surplus energy as a photon of a certain wavelength. The visible photons emitted by the most common electron jumps within excited neon atoms produce a reddish-orange glow. Street signs of other colours, erroneously called "neon," contain other gases or mixtures of gases instead of pure neon.

The Doppler Effect

The **Doppler effect** is an observed change in the wavelength of radiation caused by motion of a source or an observer relative to each other. Astronomers use it to measure the speed of blobs of gas in the Sun's atmosphere moving toward or away from Earth, as well as speeds of entire stars and galaxies.

When astronomers talk about the Doppler effect, they are talking about small shifts in the wavelength of electromagnetic radiation. The Doppler effect, however, can occur for waves of all types—sound waves, for example. You probably hear the Doppler effect in sound every day without realizing what it is. The pitch of a sound wave is determined by its wavelength. Sounds with long wavelengths have low pitches, and sounds with short wavelengths have higher pitches. You hear the Doppler effect every time a car or



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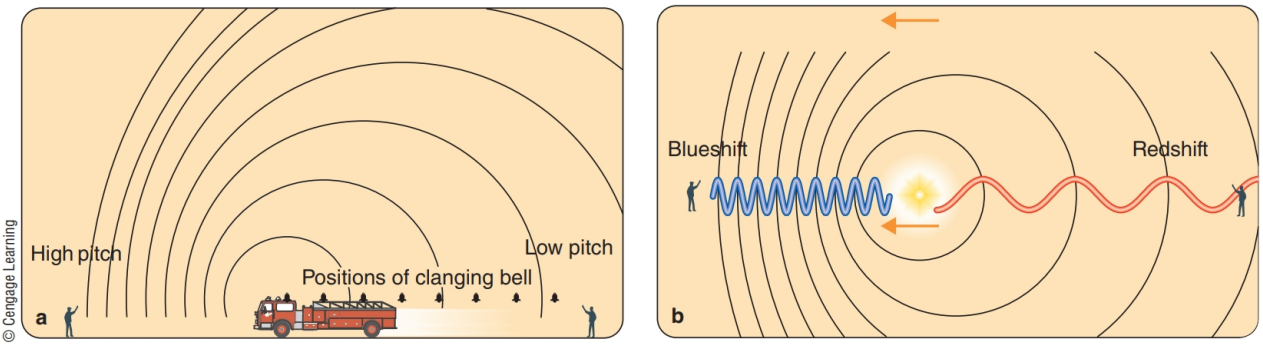
Figure 5.7 An atom can absorb a photon only if the photon has the correct amount of energy. The excited atom is unstable and within a fraction of a second returns to a lower energy level by reradiating a photon in a random direction.

ground state The lowest energy level an electron can occupy in an atom.

quantum leaps Jumps of electrons from one orbit or energy state to another.

Doppler effect The observed change in the wavelength of radiation due to a source moving toward or away from the observer.

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Figure 5.8 The Doppler effect. (a) The clanging bell on a moving fire truck produces sounds that move outward (black circles). An observer ahead of the truck hears the clangs closer together, while an observer behind the truck hears them farther apart. Similarly, the sound waves from a siren on an approaching truck will be received more often, and thus be heard with a higher pitch, than a stationary truck, and the siren will have a lower pitch if it is going away. (b) A moving source of light emits waves that move outward (black circles). An observer toward whom the light source is moving observes a shorter wavelength (a blueshift), and an observer for whom the light source is moving away observes a longer wavelength (a redshift).

truck passes you and the pitch of its engine noise or emergency siren seems to drop. Its sound is shifted to shorter wavelengths and higher pitches while it is approaching and is shifted to longer wavelengths and lower pitches after it passes by.

Understanding the Doppler effect for sound lets you understand the similar Doppler effect for light. Imagine a light source emitting waves continuously as it approaches you. The light will appear to have a shorter wavelength, making it slightly bluer. This is called a **blueshift**. A light source moving away from you has a longer wavelength and is slightly redder. This is a **redshift**. Redshifted and blueshifted spectra produced by a moving light source are illustrated in Figure 5.8.

The terms *redshift* and *blueshift* are used to refer to any range of wavelengths. The light does not actually have to be red or blue, and the terms apply equally to wavelengths in the radio, X-ray, or gamma-ray parts of the spectrum. "Red" and "blue" refer to the relative direction of the shift toward longer versus shorter wavelengths, not to actual colour. Also, note that these shifts are much too small to change the colour of a star noticeably, but they are easily detected by changes in the positions of features in a star's spectrum, such as spectral lines (discussed in detail in the next section). The Doppler shift, blue or red, reveals the relative motion of wave source and observer. You measure the same Doppler shift if the light source is moving and you are stationary or if the light source is stationary and you are moving (see Figure 5.8).

blueshift A Doppler shift toward shorter wavelengths caused by a source approaching the observer. The faster the source approaches, the larger the blueshift.

redshift A Doppler shift toward longer wavelengths caused by a source receding from the observer. The faster the source recedes, the larger the redshift.

radial velocity (V_r) The component of an object's velocity that is directed directly away from or toward Earth.

The amount of change in wavelength depends on the speed of the source. A moving car has a smaller sound Doppler shift than a jet plane, and a slow-moving star has a smaller light Doppler shift than one that is moving at high velocity. You can measure the speed of a star toward or away from you by measuring the size of the Doppler shift of its spectral lines (Figure 5.9). For an example of how to calculate the Doppler shift of an object, see the Math Reference Card on **The Doppler Formula**.

Note that the Doppler shift is sensitive only to the part of the velocity that's directed *directly* away from you or toward you; this is called the **radial velocity (V_r)**. A star moving perpendicular to your line of sight, to the left for instance, would have no blueshift or redshift because its

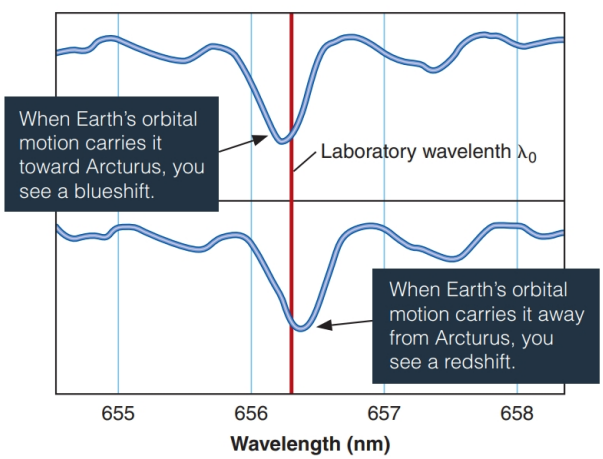


Figure 5.9 Balmer-alpha line in the spectrum of the star Arcturus.

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distance from Earth would not be decreasing or increasing. Police radar guns use the Doppler effect to measure the speeds of cars. The police park next to the highway and aim their "hair dryers" directly along the road because they can measure only radial velocities, and they want to measure your full velocity along the highway. (Refer to **The Doppler Formula** in the Math Reference Cards.)

5.5 The Sun's Atmosphere

Science is a way of understanding nature, and the spectrum of the Sun tells you a great deal about such things as the Sun's temperature and the composition and motions of the gases in the solar photosphere and atmosphere. In later chapters you will use spectra to study stars, galaxies, and planets, but you can begin with the spectrum of the Sun.

Formation of Spectra

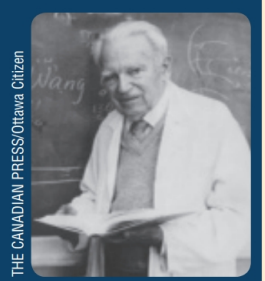
Spectra of the Sun and other stars are formed as light passes from their photospheres outward through their atmospheres. Study **Visualizing Astronomy 5.1, Atomic Spectra**, and notice three important properties of spectra:

1. There are three kinds of spectra described by three simple rules (Kirchhoff's laws). When you see one of these types of spectra, you can recognize the arrangement of matter that emitted the light. Dark (absorption) lines in the Sun's spectrum are caused by atoms in the Sun's (or Earth's) atmosphere between you and the Sun's photosphere. The photosphere itself produces a blackbody (continuous) spectrum.
2. Each type of atom has a unique absorption and emission spectrum. Hence, we can distinguish hydrogen from helium or other gases by observing the spectrum of the Sun. The wavelengths of the photons that are absorbed by a given type of atom are the same as the wavelengths of the photons emitted by that type of atom; both are determined by the electron energy levels in the atom. The emitted photons coming from a hot cloud of hydrogen gas have the same wavelengths as the photons absorbed by hydrogen atoms in the Sun's atmosphere. Although the hydrogen atom produces many spectral lines from the ultraviolet to the infrared, only three hydrogen lines are visible to human eyes.
3. Most modern astronomy books display spectra as graphs of intensity versus wavelength. Be sure you see the connection between dark absorption lines and dips in the graphed spectrum.

The Sun's Chemical Composition

Identifying the elements in the Sun's atmosphere by identifying the lines in its spectrum is a relatively straightforward

CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



THE CANADIAN PRESS/Ottawa Citizen

Gerhard Herzberg

Gerhard Herzberg

Nobel Prize–winning physicist Gerhard Herzberg recalled arriving in Saskatoon from Germany in 1935 with barely $2.50 in his pocket. Despite being a leading molecular physicist at the time, he was forced to leave Nazi Germany and decided to accept a position at the University of Saskatchewan. Over the next decade he continued his spectroscopic studies of atomic and molecular structure, writing several classic books on the subject. One of his early successes was the application of his methods to identify the molecule CH^+ in interstellar clouds. Dr. Herzberg subsequently worked at the University of Chicago's Yerkes Observatory for three years, fulfilling his past ambition of being an astronomer. There he developed novel methods to study planetary atmospheres and comets, which became standard techniques widely used around the world. When he returned to Canada in 1948, he joined the National Research Council (NRC) and helped make it a world leader in molecular spectroscopy. His research group made several important scientific discoveries including the detection of hydrogen in the atmospheres of planets and the presence of water in comets. Dr. Herzberg was awarded the Nobel Prize in chemistry in 1971 for his contributions to molecular spectroscopy. Today, the Herzberg Canada Gold Medal is the highest honour for science and engineering in Canada, awarded annually in his memory by the Natural Sciences and Engineering Research Council (NSERC) of Canada.

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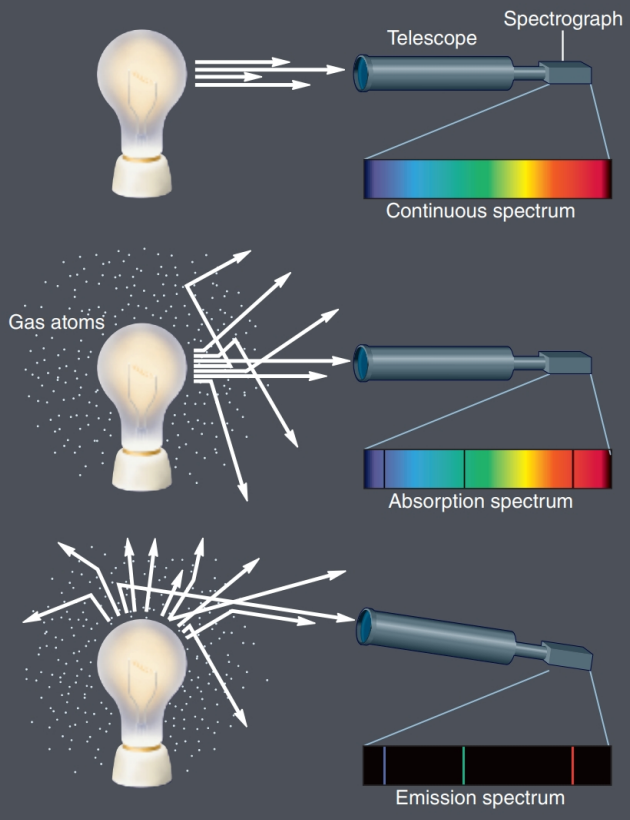
Visualizing Astronomy 5.1
Atomic Spectra

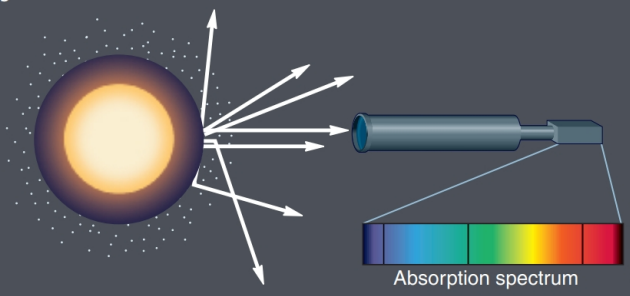
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To understand how to analyze a spectrum, begin with a simple incandescent light bulb. The hot filament emits blackbody radiation, which forms a **continuous spectrum**.

An **absorption spectrum** results when radiation passes through a cool gas. In this case you can imagine that the light bulb is surrounded by a cool cloud of gas. Atoms in the gas absorb photons of certain wavelengths that are then missing from the observed spectrum, and you see dark **absorption lines** at those wavelengths. Such absorption spectra are also called **dark-line spectra**.

An **emission spectrum** is produced by photons emitted by an excited gas. You could see **emission lines** by turning your telescope aside so that photons from the bright bulb do not enter the telescope and the excited gas has a dark background. The photons you would see would be those emitted by the excited atoms near the bulb, and the observed spectrum is mostly dark with a few bright emission lines. Such spectra are also called **bright-line spectra**.





1a The spectrum of a star is an absorption spectrum. The denser layers of the photosphere emit blackbody radiation. Gases in the atmosphere of the star absorb their specific wavelengths and form dark absorption lines in the spectrum.

Science & Society Picture Library/Getty Images



1b In 1859, long before scientists understood atoms and electron energy levels, the German scientist Gustav Kirchhoff formulated three rules—now known as **Kirchhoff's laws**—describing the three types of spectra.

KIRCHHOFF'S LAWS

Law I: The Continuous Spectrum

A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a continuous spectrum.

Law II: The Emission Spectrum

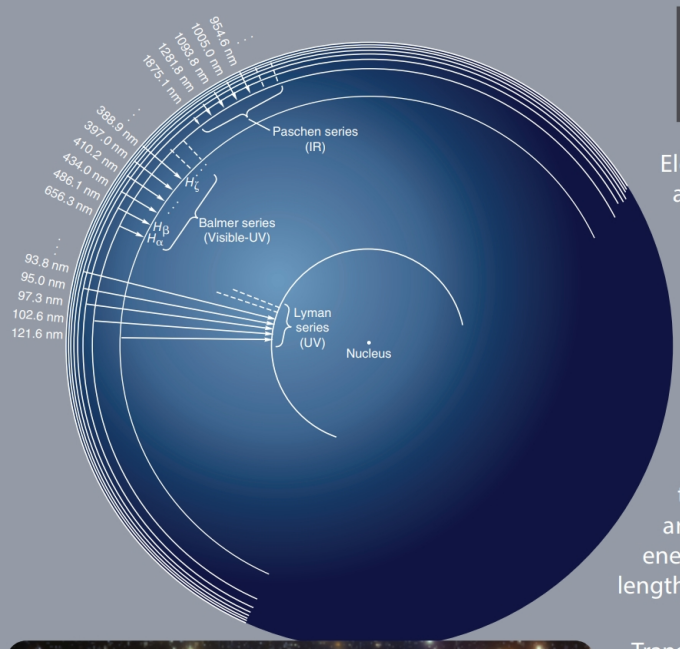
A low-density gas excited to emit light will do so at specific wavelengths and thus produce an emission spectrum.

Law III: The Absorption Spectrum

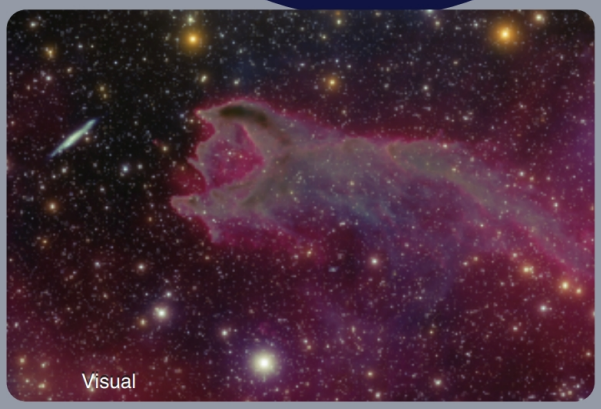
If light comprising a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum.

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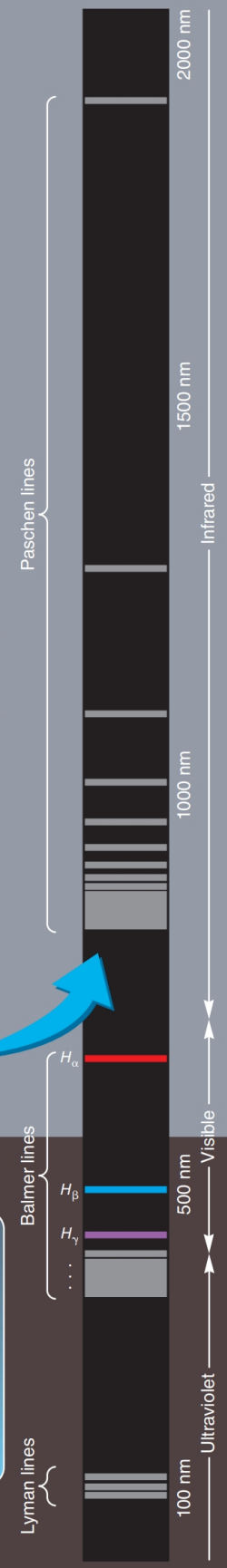
2 Electron orbits in the hydrogen atom are shown here as energy levels. When an electron makes a **transition** from one orbit to another, this means that the energy stored in the atom has changed. In this diagram, arrows pointed inward toward the nucleus represent transitions that result in the emission of a photon. If the arrows pointed outward, they would represent transitions that result from the absorption of a photon. Long arrows represent large amounts of energy and correspondingly short-wavelength photons.



T.A. Rector/University of Alaska Anchorage, T. Abbott and NOAO/AURA/NSF

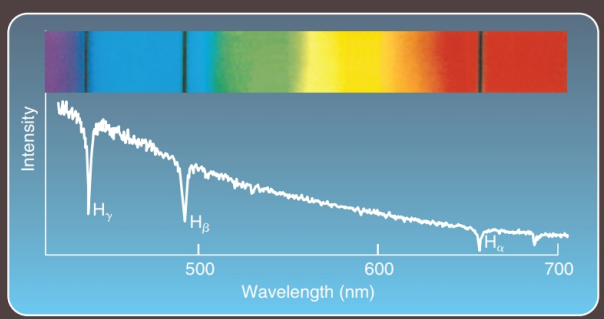
2a Transitions in the hydrogen atom can be grouped into series—the **Lyman series**, **Balmer series**, **Paschen series**, and so on, named after scientists who carefully investigated the spectra of hydrogen atoms. Transitions and the resulting spectral lines are identified by Greek letters. Only the first few transitions in the first three series are shown at left.

2b In this drawing (*right*) of the hydrogen spectrum, emission lines in the infrared and ultraviolet are shown as grey. Only the first three lines of the Balmer series are visible to human eyes.



2c Excited clouds of gas in space emit light at all of the Balmer wavelengths, but you see only the red, blue, and violet photons blending to create the purple-pink colour typical of ionized hydrogen.

3 Modern astronomers rarely work with spectra in the form of images of bands of light. Spectra are usually recorded digitally, so it is easy to represent them as graphs of intensity versus wavelength. Here, the artwork above the graph suggests the appearance of a stellar spectrum. The graph at right reveals details not otherwise visible and allows comparison of relative intensities. Notice that dark absorption lines in the spectrum appear as dips in the intensity graph.



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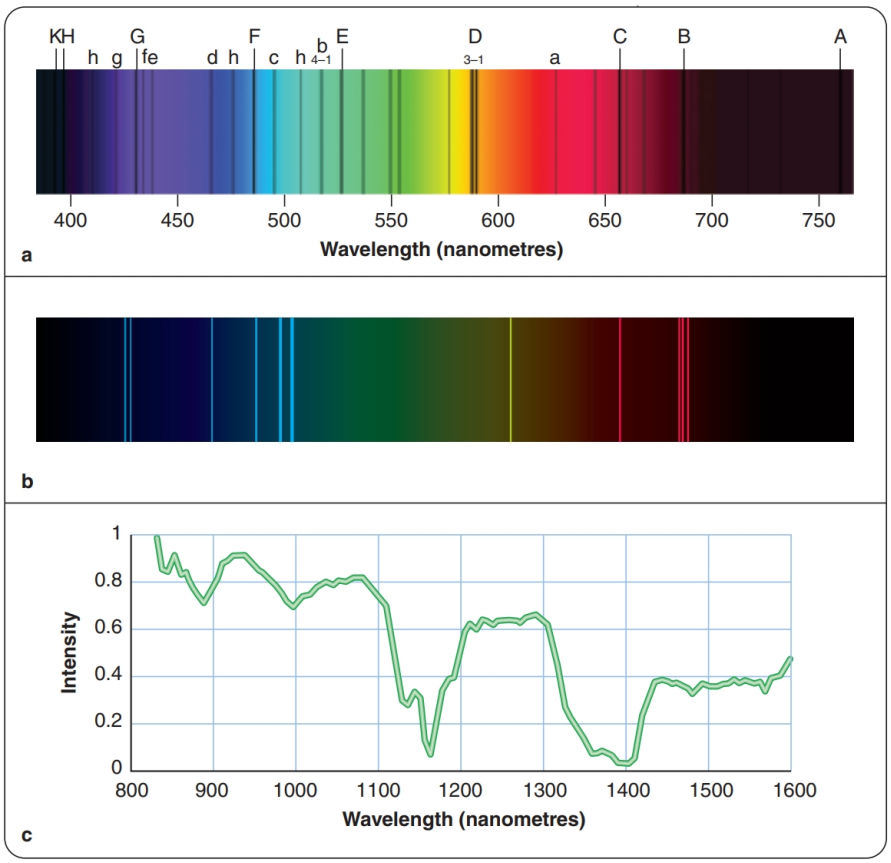


Figure 5.10 (a) The Sun's spectrum at visual wavelengths. The bright coloured background shows the continuous spectrum of blackbody emission from the Sun's photosphere. The dark spectral absorption lines represent precise colours (photons of exact energies) absorbed from the Sun's radiation by atoms in its atmosphere. (b) A model of the visual wavelength emission (bright-line) spectrum of NCG2392. Emission lines from ionized atoms of hydrogen (red), nitrogen (red), and oxygen (green), among others, are seen. (c) Near-infrared spectrum of the atmosphere and surface of Saturn's moon Titan measured by the Huygens probe at an altitude of 20 m using a light source on the bottom of the probe.

procedure (Figure 5.10a). For example, two dark absorption lines appear in the yellow region of the solar spectrum at the wavelengths 589.0 nm and 589.6 nm. The only atom that can produce this pair of lines is sodium, so the Sun must contain sodium. Over 90 elements in the Sun have been identified this way. The element helium was observed in the Sun's spectrum first, before helium (from the Greek word *helios,* meaning "sun") was found on Earth.

However, just because spectral lines that are characteristic of an element are missing, you cannot conclude that the element itself is absent. For example, although more than 90 percent of the atoms in the Sun are hydrogen, the hydrogen Balmer lines are weak in the Sun's spectrum (refer to **Visualizing Astronomy 5.1, Atomic Spectra**). The reason for this apparent paradox is that the Sun is too cool to produce strong Balmer lines. At the Sun's photosphere temperature, atoms do not usually collide violently enough to knock electrons in hydrogen atoms into the second energy level, which is the necessary starting place for Balmer line absorptions. Spectral lines of other varieties of atoms (for example, ionized calcium) are especially easy to observe in the Sun's spectrum because the Sun is the right temperature to excite those atoms to the energy levels that can produce visible spectral lines, even though those atoms are not very common in the Sun.

chromosphere Bright gases just above the photosphere of the Sun.

The effect of temperature on the visibility of spectral lines was first understood by Cecila Payne (later, Payne-Gaposchkin), who was an astronomer doing Ph.D. research work at Harvard Observatory in the 1920s (Figure 5.11). She used the new techniques of quantum mechanics to derive accurate chemical abundances for the Sun and other stars; she was the first person to know that the Sun is mostly composed of hydrogen, even though its visible-wavelength hydrogen spectral lines are only moderately strong.

Astronomers must use the physics that describes the interaction of light and matter to analyze a star's spectrum, taking into account the star's temperature, to calculate correctly the amounts of each element present in the star. Such results show that nearly all stars have compositions similar to the Sun—about 90 percent of the atoms are hydrogen, and about 9 percent are helium, with small traces of heavier elements (Table 5.1). It is fair to say that Cecilia Payne, whose thesis has been called the most important doctoral work in the history of astronomy, figured out the true chemical composition of the universe. You will use her results in later chapters when you study the life stories of the stars, the history of our galaxy, and the origin of the universe.

The Chromosphere

Above the photosphere lies the **chromosphere**. Solar astronomers define the lower edge of the chromosphere

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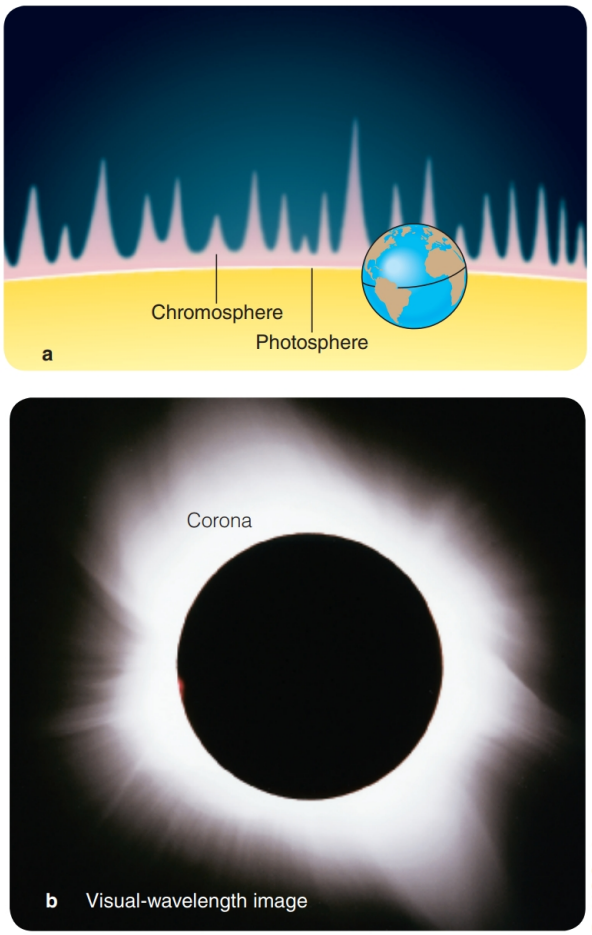
Figure 5.11 Dr. Cecilia Payne-Gaposchkin first discovered that the Sun and other stars are mostly made of hydrogen. Her Ph.D. thesis has been called the most important in the history of astronomy.

as lying just above the visible surface of the Sun with its upper regions blending gradually with the atmosphere's outermost layer, the **corona**, which is described later in this chapter.

You can think of the chromosphere as being an irregular layer with a depth on average less than Earth's diameter (Figure 5.12). Because the chromosphere is roughly 1000 times fainter than the photosphere, you can see it with your unaided eyes only during a total solar eclipse when the Moon covers the brilliant photosphere. Then, the chromosphere flashes into view as a thin line of pink just above the photosphere. The word *chromosphere* comes from the Greek word *chroma*, meaning "colour." The pink colour

Table 5.1 The Most Abundant Elements in the Sun

Element	Percentage by Number of Atoms	Percentage by Mass
Hydrogen	91.0	70.9
Helium	8.9	27.4
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.07	0.8
Neon	0.01	0.2
Magnesium	0.003	0.06
Silicon	0.003	0.07
Sulphur	0.002	0.04
Iron	0.003	0.1



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Daniel C. Good

Figure 5.12 (a) A cross-section at the edge of the Sun shows the relative thickness of the photosphere and chromosphere. Earth is shown for scale. On this scale, the disk of the Sun would be more than 1.5 m in diameter. (b) The corona extends from the top of the chromosphere to a great distance above the photosphere. This photograph, made during a total solar eclipse, shows only the inner part of the corona.

is produced by combined light of three bright emission lines—the red, blue, and violet Balmer lines of hydrogen.

Astronomers know a great deal about the chromosphere from its spectrum. The chromosphere produces an emission spectrum, and Kirchhoff's second law tells you the chromosphere must be an excited, transparent, low-density gas viewed with a dark, cold background (see **Visualizing Astronomy 5.1, Atomic Spectra**). The density is about 100 million times less than that of the air you breathe.

Atoms in the lower chromosphere are ionized, and atoms in the higher layers of the chromosphere are even more highly ionized. That is, they have lost more

corona The faint outer atmosphere of the Sun, composed of low-density, high-temperature gas.

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electrons. From this, astronomers can find the temperature in different parts of the chromosphere. Just above the photosphere, the temperature falls to a minimum of about 4500 K and then rises to the extremely high temperatures of the corona.

Solar astronomers can take advantage of some of the physics of spectral line formation to study the chromosphere. A photon with a wavelength corresponding to one of the solar atmosphere's strong absorption lines is very unlikely to escape from deeper layers and reach Earth since it is likely to be absorbed by the solar atmosphere. A **filtergram** is a photograph made using light in one of those dark absorption lines. Those photons can only come from high in the solar atmosphere. In this way, filtergrams reveal detail in the upper layers of the chromosphere. In a similar way, an image recorded in the far-ultraviolet or in the X-ray part of the spectrum reveals other structures in the hottest parts of the solar atmosphere.

Figure 5.13a shows a filtergram made at the wavelength of the H_α Balmer line. This image shows complex structure in the chromosphere, including long, dark **filaments** silhouetted against the brighter surface. **Spicules** are flamelike jets of gas extending upward into the chromosphere and lasting 5 to 15 minutes. Figure 5.13b shows how, at the limb of the Sun's disk, the spicules blend together and look like flames covering a burning prairie, but they are not flames at all. Spectra show that spicules are cooler gas from the lower chromosphere extending upward into hotter regions.

Spectroscopic analysis of the chromosphere shows that it is a low-density gas in constant motion, and its temperature increases rapidly with height. Just above the chromosphere lies even hotter gas.

filtergram A photograph (usually of the Sun) taken in the light of a specific region of the spectrum; for example, an H_α filtergram.

filament A solar eruption, seen from above, silhouetted against the bright photosphere.

spicule A small, flamelike projection in the chromosphere of the Sun.

coronagraph A telescope designed to capture images of faint objects, such as the corona of the Sun, that are near relatively bright objects.

The Corona

The outermost part of the Sun's atmosphere is called the *corona*, after the Greek word for "crown." The corona is so dim that it is not visible in Earth's daytime sky because of the glare of scattered light from the Sun's brilliant photosphere. During a total solar eclipse, however, when the Moon covers the photosphere, you can see the innermost parts of the corona, as shown in Figure 5.12b. Observations made with specialized telescopes called **coronagraphs** on Earth or in space can block the light of the photosphere and record the corona out beyond 20 solar radii, almost 10 percent of the way to Earth. Such images reveal that sunspots are linked with features in the chromosphere and corona (Figure 5.14).

The spectrum of the corona can tell you a great deal about the coronal gases and simultaneously illustrate how astronomers analyze a spectrum. Some of the light

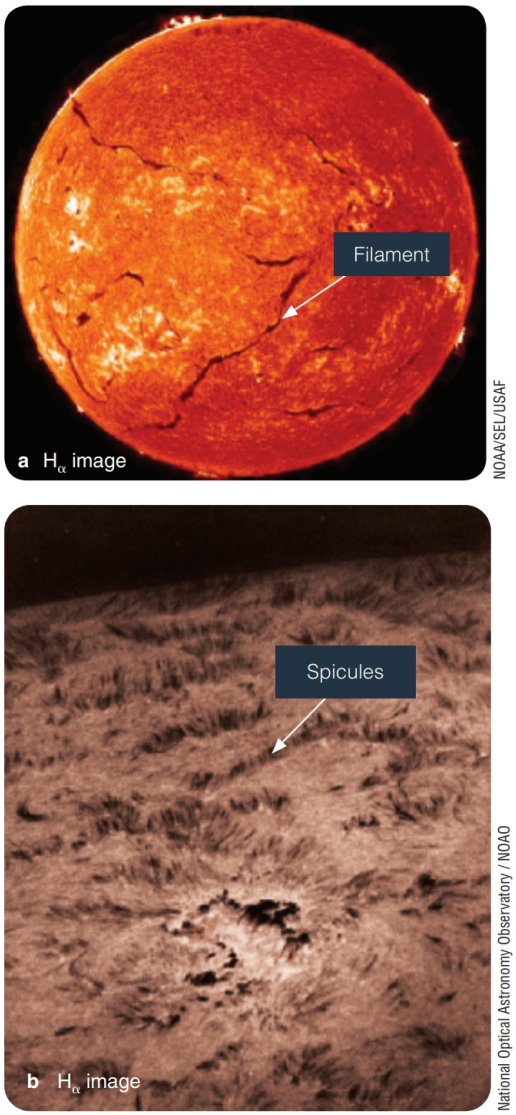


Figure 5.13 H_α filtergrams reveal complex structures in the chromosphere, including (a) long, dark filaments and (b) spicules springing from the edges of supergranules that are larger than twice the diameter of Earth.

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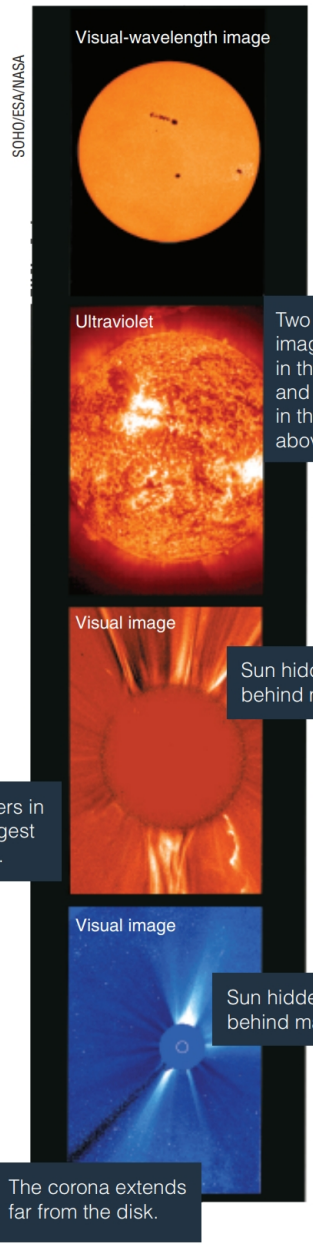


Figure 5.14 Images of the photosphere, chromosphere, and corona show the relationship among the layers of the Sun's atmosphere. The visual wavelength image shows the Sun in white light—that is, as you would see it with your eyes.

from the corona produces a continuous spectrum that lacks absorption lines. Superimposed on the corona's continuous spectrum are emission lines of highly ionized gases. In the lower corona, the atoms are not as highly ionized as they are at higher altitudes, and this tells you that the temperature of the corona rises with altitude. Just above the chromosphere, the coronal temperature is about 500 000 K, but in the outer corona the temperature can be 2 000 000 K or more. Despite that very high temperature, the corona does not produce much light because its density is very low, only 10^6 atoms/cm^3 or less. That is about one-trillionth the density of the air you breathe.

Astronomers have wondered for years how the corona and chromosphere can be so hot. Heat flows from hot regions to cool regions, never from cool to hot. So how can the heat from the photosphere, with a temperature of only 5800 K, flow out into the much hotter chromosphere and corona? Observations made by the SOHO satellite show a **magnetic carpet** of looped magnetic fields extending up through the photosphere. A magnetic field is a region in which a magnetic substance (such as iron, for example) will feel a magnetic force. If you sprinkle iron filings on a paper placed above a bar magnet, the iron filings align themselves along curved loops connecting the north and south poles. These loops show magnetic field lines running from the north pole to the south pole of the magnet. The lines map out the direction and strength of the magnetic force at each point. Remember that the gas of the chromosphere and corona has a very low density, so it can't resist movement in the magnetic fields. Turbulence below the photosphere seems to flick the magnetic loops back and forth and whip the gas about. That heats the gas. In this instance, energy appears to flow outward in the form of agitation of the magnetic fields. Solar magnetic phenomena will be discussed more thoroughly later in this chapter.

Not all of the Sun's magnetic field loops back toward the Sun; some of the field lines lead outward into space. Gas from the solar atmosphere follows along the magnetic fields that point outward and flows away from the Sun in a breeze called the **solar wind** that can be considered an extension of the corona. The low-density gases of the solar wind blow past Earth at 300 to 800 km/s with gusts as high as 1000 km/s (Figure 5.15).

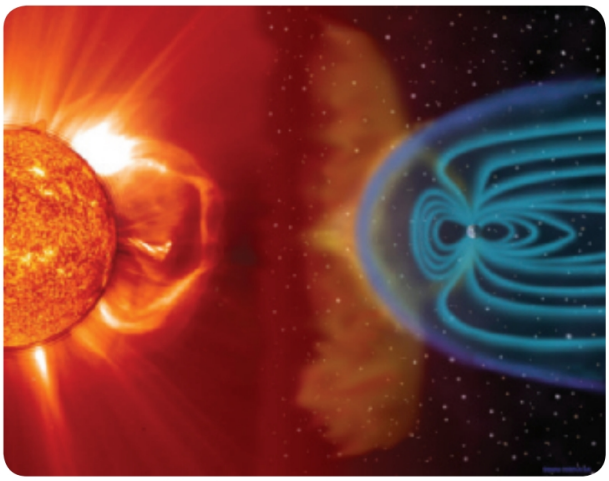
Because of the solar wind the Sun is slowly losing mass, but this is a minor loss for an object as massive as the Sun. The Sun loses about a hundred million tons per second, but that is only 10^{-14} of the solar mass per year. Later in life, the Sun, like many other stars, will lose mass rapidly. You will see in future chapters how this affects the evolution of stars.

Do other stars have chromospheres, coronae, and stellar winds like the Sun? Ultraviolet and X-ray observations suggest that the answer is yes. The spectra of many stars contain emission lines in the far-ultraviolet that could only have formed in the low-density, high-temperature gases of a chromosphere or corona. Also, many stars are sources of X-rays that appear to have been produced by the high-temperature gas in coronae. This observational evidence gives astronomers good reason to believe that the Sun, for all its complexity, is a typical star.

magnetic carpet The network of small magnetic loops that covers the solar surface.

solar wind Rapidly moving atoms and ions that escape from the solar corona and blow outward through the solar system.

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SOHO (ESA & NASA)

Figure 5.15 Earth's magnetic field is our shield against the harmful effects of the solar wind.

5.6 Solar Activity

The Sun is not quiet. It is home to slowly changing spots larger than Earth and rapid, vast eruptions that dwarf human imagination. All of these seemingly different forms of solar activity have one thing in common: magnetic fields.

Observing the Sun

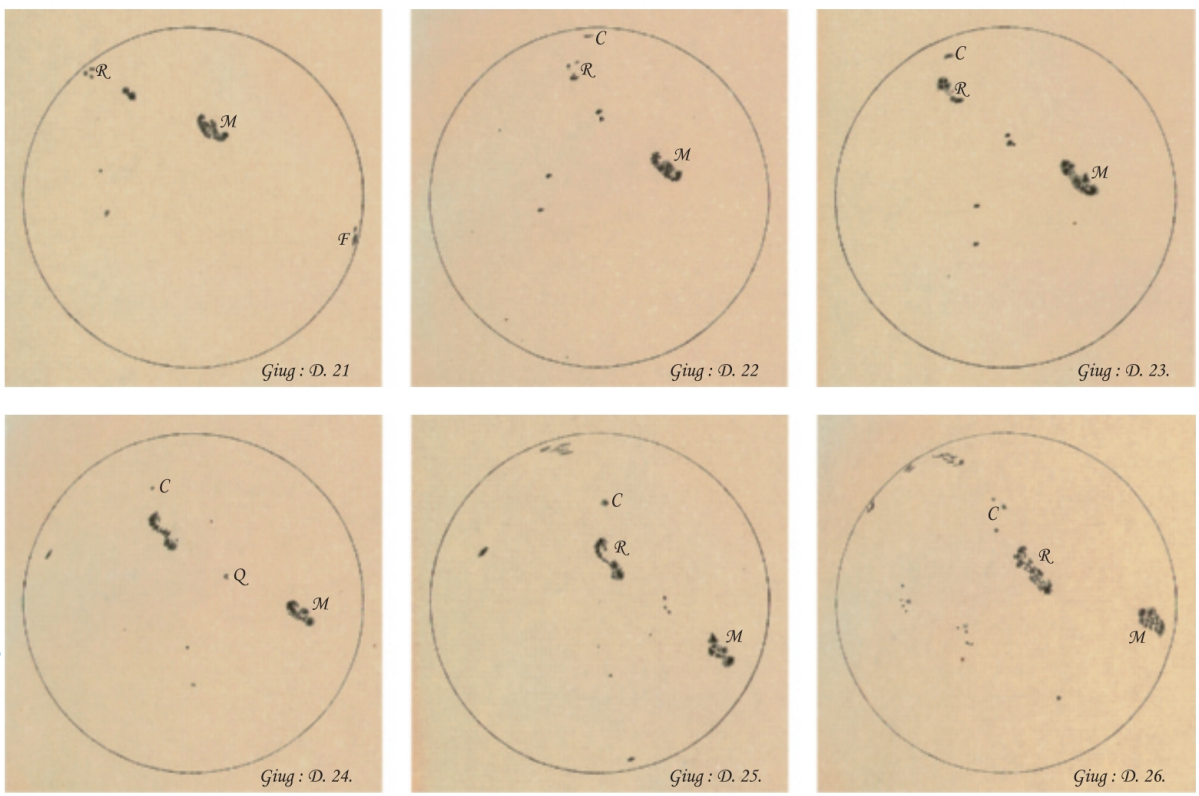
Solar activity is often visible with even a small telescope, but you should be very careful about observing the Sun. It is not safe to look directly at the Sun, and it is even more dangerous to look at the Sun through any optical instrument such as a telescope, binoculars, or even the viewfinder of a camera. These concentrate sunlight and can cause severe injury. You can safely project an image of the Sun onto a screen, or you can use specially designed solar blocking filters.

In the early 17th century, Galileo observed the Sun and saw spots on its surface; day by day, he saw the spots moving across the Sun's disk. He correctly concluded that the Sun is a sphere and is rotating (Figure 5.16).

Sunspots

The dark sunspots that you see at visible wavelengths only hint at the complex processes that go on in the Sun's atmosphere. To explore those processes, you must turn to the analysis of images and spectra at a wide range of wavelengths. Study **Visualizing Astronomy 5.2, Sunspots and the Sunspot Cycle**, and notice five important points:

1. Sunspots are cool spots on the Sun's surface caused by strong magnetic fields.



Collection of Owen Gingerich

Figure 5.16 If you sketch the location and structure of sunspots on successive days you will see the rotation of the Sun and gradual changes in the size and structure of sunspots, just as Galileo did in 1612.

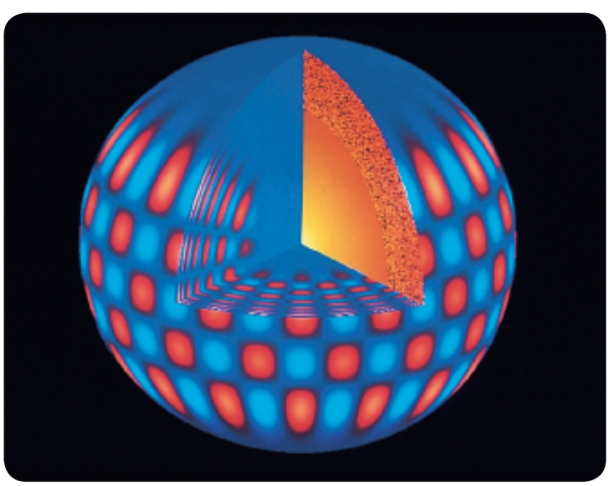
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2. Sunspots follow an 11-year cycle not only in the number of spots visible but also in their location on the Sun.
3. The Zeeman effect gives astronomers a way to measure the strength of magnetic fields on the Sun.
4. Characteristics of the sunspot cycle vary over centuries and appear to affect Earth's climate.
5. Finally, there is clear evidence that sunspots are part of a larger magnetic process that involves other layers of the Sun's atmosphere and parts of its interior.

The sunspot groups are merely the visible traces of magnetically active regions. But what causes this magnetic activity? The answer appears to be linked to the cyclical strengthening and weakening of the Sun's overall magnetic field.

Insight into the Sun's Interior

Almost no light emerges from below the photosphere, so you can't see into the solar interior. However, solar astronomers can use the vibrations in the Sun to explore its depths in a type of analysis called **helioseismology**. Random motions in the Sun constantly produce vibrations. Astronomers can detect these vibrations by observing Doppler shifts in the solar surface. These waves make the photosphere move up and down by small amounts—roughly plus or minus 15 km. This covers the surface of the Sun with a pattern of rising and falling regions that can be mapped, as shown in Figure 5.17. In the Sun, a vibration with a period of 5 minutes is strongest, but other periods are observed ranging from 3 to 20 minutes. Just as geologists can study Earth's interior by analyzing vibrations from earthquakes, so solar astronomers can use helioseismology to map the temperature, density, and rate of rotation in the Sun's invisible interior.



AURA/NOAO/NSO

Figure 5.17 The Sun can vibrate in millions of different patterns or modes, and each mode corresponds to a different vibration wavelength that penetrates to a different level in the solar interior. By measuring Doppler shifts produced as the photosphere moves gently up and down, astronomers can map the inside of the Sun.

The Global Oscillation Network Group (GONG) is a worldwide network of observatories located in Australia, India, the United States, Chile, and the Canary Islands that makes continuous observations of "sunquakes"—the vibrations of the Sun. Large-scale collaborations of this type are increasingly common in current astronomy research efforts and are critical for our shared goal of understanding our Sun, our solar system, and our universe.

The Sun's Magnetic Cycle

Sunspots are magnetic phenomena, so the 11-year cycle of sunspots must be caused by cyclical changes in the Sun's magnetic field. To explore that idea, you can begin with the Sun's rotation.

The Sun does not rotate as a rigid body. It is a gas from its outermost layers down to its centre, and some parts of the Sun rotate faster than other parts. Figure 5.18 demonstrates how the equatorial region of the photosphere rotates faster than do regions at higher latitudes. At the equator, the photosphere rotates once every 25 days, but at latitude 45° one rotation takes 28 days. Helioseismology can map the rotation throughout the interior (Figure 5.18b). This phenomenon is called **differential rotation**, and it is clearly linked with the magnetic cycle.

The Sun's magnetic field appears to be powered by the energy flowing outward through the moving currents of gas. The gas is highly ionized, so it is a very good conductor of electricity. When an electrical conductor rotates rapidly and is stirred by convection, it can convert some of the energy flowing outward as convection into a magnetic field. This process is called the **dynamo effect**, and it is believed to operate also in the liquid metal of Earth's core to produce Earth's magnetic field. Helioseismology observations have found evidence that the Sun's magnetic field is generated by the dynamo effect at the bottom of the **convective zone** deep under

helioseismology The study of the interior of the Sun by the analysis of its modes of vibration.

differential rotation The rotation of a body in which different parts of the body have different periods of rotation. This is true of the Sun, the Jovian planets, and the disk of the galaxy.

dynamo effect The process by which a rotating, convecting body of conducting matter, such as Earth's core, can generate a magnetic field.

convective zone The region inside a star where energy is carried outward as rising hot gas and sinking cool gas.

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Visualizing Astronomy 5.2

Sunspots and the Sunspot Cycle

1

The dark spots that appear on the Sun are only the visible traces of complex regions of activity. Evidence gathered over many years and at a wide range of wavelengths shows that sunspots are clearly linked to the Sun's magnetic field.

Spectra show that sunspots are cooler than the photosphere with a temperature of about 4200 K. The photosphere has an average temperature of about 5800 K. Because, according to the Stefan–Boltzmann law, the total amount of energy radiated by a surface depends on its temperature raised to the fourth power, sunspots look dark in comparison with the photosphere. Actually, a sunspot emits quite a bit of radiation. If the Sun were removed and only an average-size sunspot were left behind, it would be brighter than a full moon.

A typical sunspot is about twice the size of Earth, but there is a wide range of sizes. They appear, last a few weeks to as long as 2 months, and then shrink away. Usually, sunspots occur in pairs or complex groups.



NASA

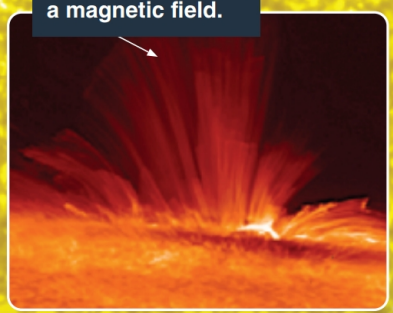
Umbra

Penumbra

Sunspots are not shadows, but astronomers refer to the dark core of a sunspot as its umbra and the outer, lighter region as the penumbra.

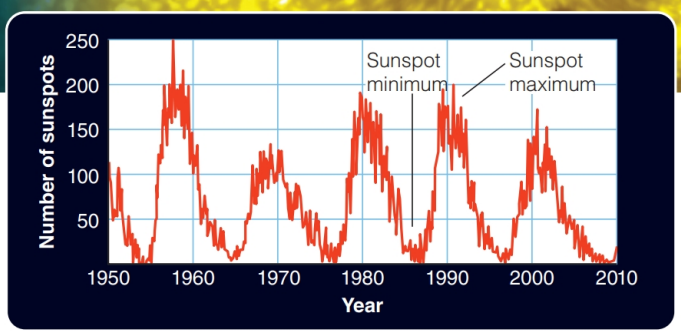
JAXA/NASA/Hinode

Streamers above a sunspot suggest a magnetic field.



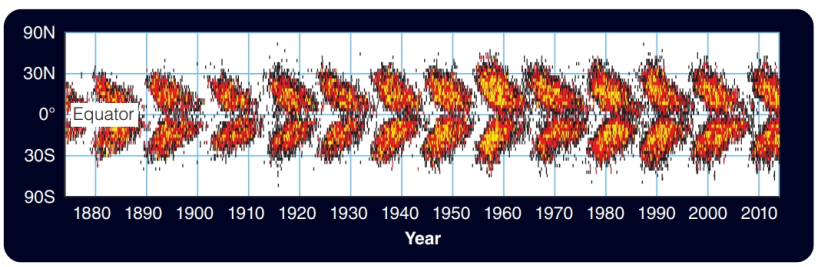
Hinode JAXA/NASA

Visual



2

The number of spots visible on the Sun varies in a cycle with a period of 11 years. At maximum, there are often more than 100 spots visible. At minimum, there are very few.



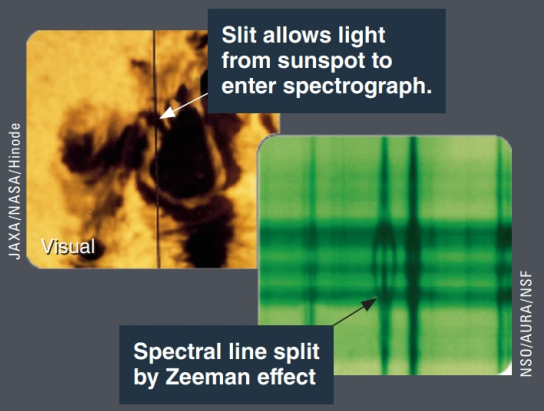
D. Hathaway NASA/MSFC

2a Early in a cycle, spots appear at high latitudes north and south of the Sun's equator. Later in the cycle, new spots appear closer to the Sun's equator. If you plot the latitude of sunspots versus time, the graph looks like butterfly wings, as shown in this **Maunder butterfly diagram**, named after E. Walter Maunder of Greenwich Observatory.

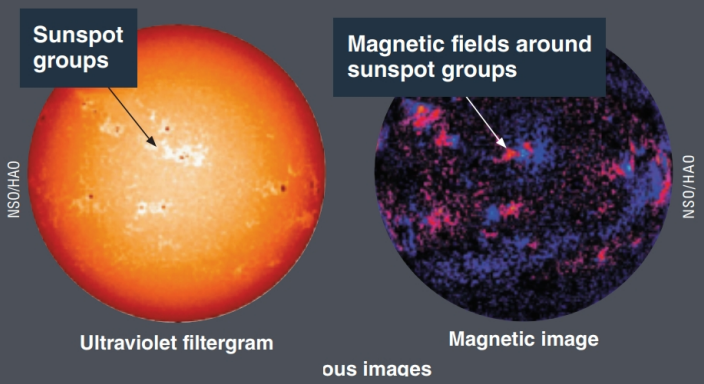
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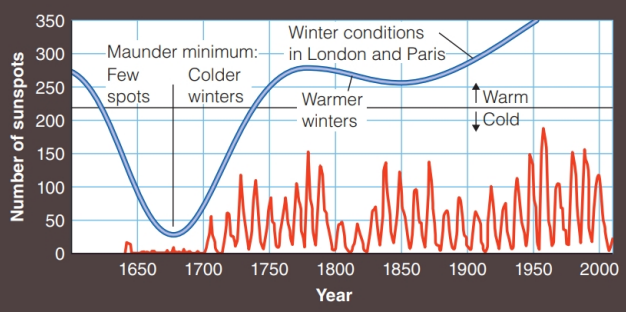
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3 Astronomers can measure magnetic fields on the Sun using the **Zeeman effect**, as shown alongside. When an atom is in a magnetic field, the electron energy levels are altered, and the atom is able to absorb photons with a greater variety of wavelengths than the same atom not in a magnetic field. In this spectrum you see single spectral lines split into multiple components, with the separation between the components proportional to the strength of the magnetic field.



3a Images of the Sun on the right show that sunspots contain magnetic fields a few thousand times stronger than Earth's. Such strong fields inhibit motions of ionized gas below the photosphere; consequently, convection is reduced below the sunspot, less energy is transported from the interior, and the Sun's surface at the position of the spot is cooler. Heat that is prevented from emerging at the sunspot's position is deflected and emerges around the sunspot, making the surrounding area hotter than the average photosphere. The deflected heat can be detected in ultraviolet and infrared images; the result is that the entire active region, including the sunspots, is actually emitting more energy than the same area of normal photosphere.

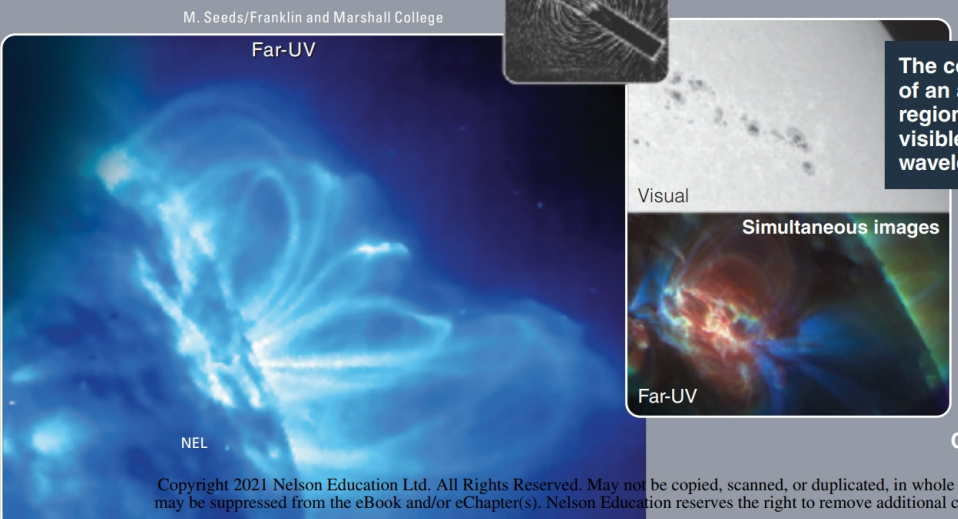




4 Historical records show that there were very few sunspots from about 1645 to 1715, a phenomenon known as the **Maunder minimum**. This coincides with the middle of a period called the "Little Ice Age," a time of unusually cool weather in Europe and North America from about 1500 to about 1850, as shown in the graph at left. Other such periods of cooler climate are known. Evidence suggests that there is a link between solar activity and the amount of solar energy Earth receives. This link has been confirmed by measurements made by spacecraft above Earth's atmosphere.

5 Observations at nonvisual wavelengths reveal that the chromosphere and corona above sunspots are violently disturbed in what astronomers call **active regions**. Spectrographic observations show that active regions contain powerful magnetic fields. If all wavelengths are included, Earth receives more radiation from the spotted, active Sun than at times of low activity.

Arched structures above an active region are evidence of gas trapped in magnetic fields.



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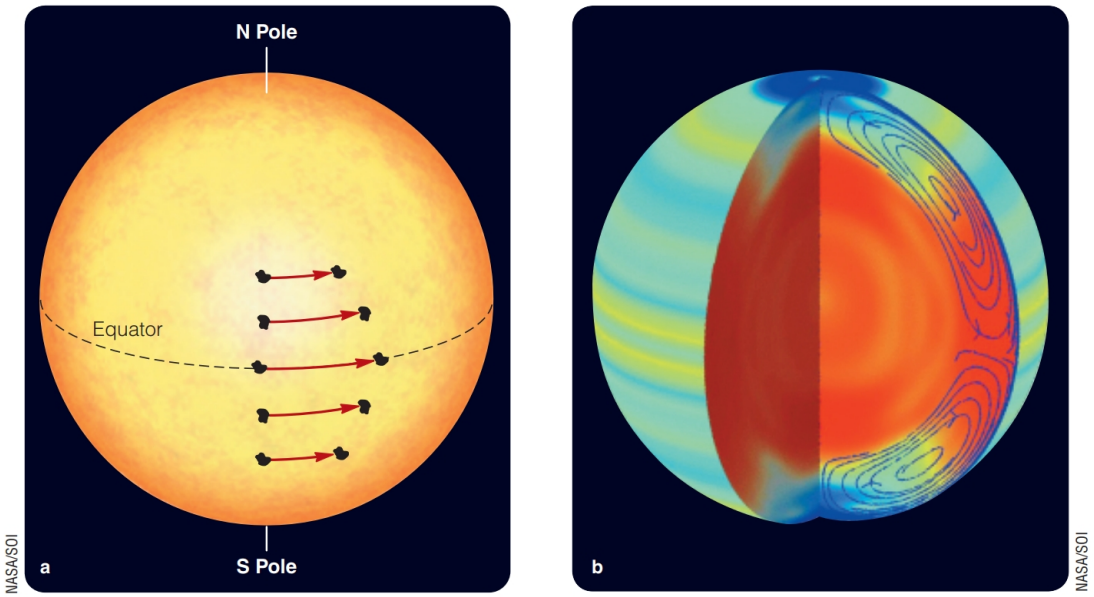


Figure 5.18 (a) In general, the photosphere of the Sun rotates faster at the equator than at higher latitudes. If you observed five sunspots in a row, they would not stay lined up as the Sun rotates. (b) Detailed analyses of the Sun's interior rotation from helioseismology reveal regions of slow rotation (blue) and rapid rotation (red). Such studies show that differential rotation occurs inside the Sun as well as on its surface.

the photosphere. The Sun's magnetic cycle is related to how its magnetic field is created.

The magnetic behaviour of sunspots provides an insight into how the magnetic cycle works. Sunspots tend to occur in groups or pairs, and the magnetic field around the pair resembles that around a bar magnet with one end magnetic north and the other end magnetic south. At any one time, sunspot pairs south of the Sun's equator have reversed polarity compared to those north of the Sun's equator. Figure 5.19 illustrates this by showing sunspot pairs south of the Sun's equator with magnetic south poles leading and sunspots north of the Sun's equator with magnetic north poles leading. At the end of an 11-year sunspot cycle, the new spots appear with reversed magnetic polarity.

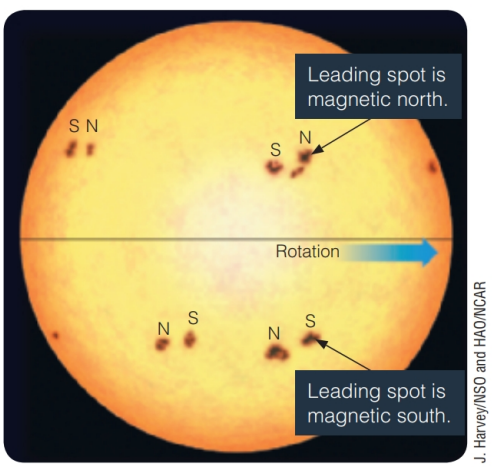


Figure 5.19 In sunspot groups, here simplified into pairs of major spots, the leading spot and the trailing spot have opposite magnetic polarity. Spot pairs in the southern hemisphere have reversed polarity from those in the northern hemisphere.

The Sun's magnetic cycle is not fully understood, but is thought to be due to a progressive tangling and then untangling of the solar magnetic field, as demonstrated in Figure 5.20.

If the Sun is truly a representative star you might expect to find similar magnetic cycles on other stars, but they are too distant for spots to be directly visible. Some stars, however, vary in brightness over a period of days, in a way revealing that they are marked with dark spots believed to resemble sunspots. Other stars have features in their spectra that vary over periods of years, suggesting that they are subject to magnetic cycles much like the Sun's cycle. Once again, the evidence tells you that the Sun is a normal star.

Chromospheric and Coronal Activity

The solar magnetic fields extend high into the chromosphere and corona, where they produce beautiful and powerful phenomena. Study **Visualizing Astronomy 5.3, Magnetic Solar Phenomena**, and notice three important points:

1. All solar activity is magnetic. You do not experience such events on Earth because Earth's magnetic field is

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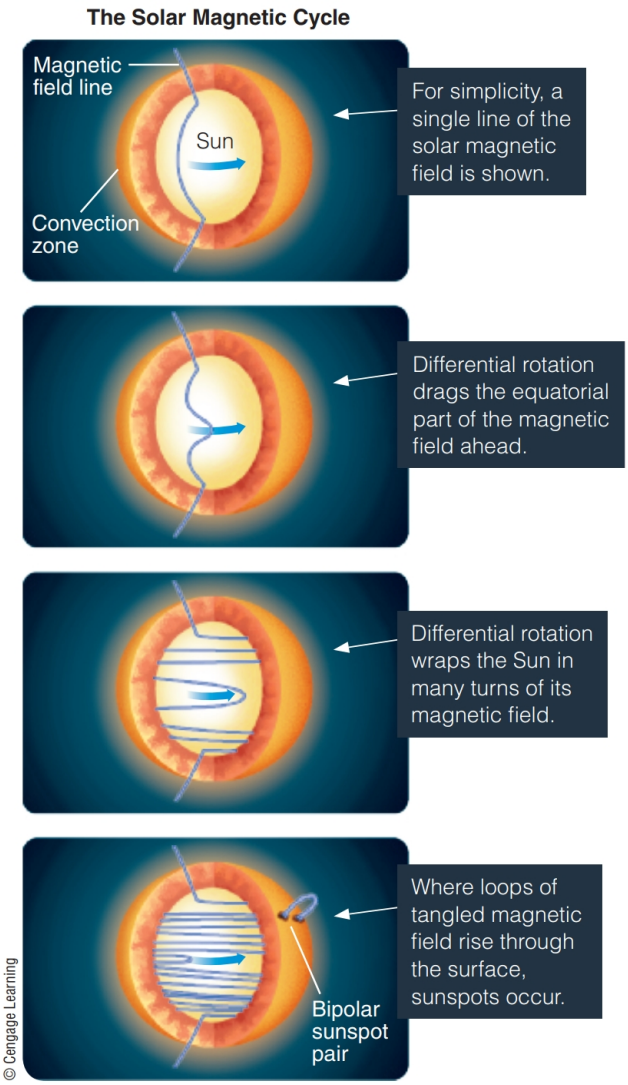


Figure 5.20 The sunspot cycle may be a consequence of the Sun's differential rotation gradually winding up the magnetic field near the base of the Sun's outer, convective layer.

weak and Earth's atmosphere is not ionized, so it is free to move independent of the magnetic field. On the Sun, however, the "weather" is a magnetic phenomenon.

2. Tremendous energy can be stored in arches of magnetic fields. These are visible near the edge of the solar disk as prominences, and, seen from above, as filaments. When that stored energy is released, it can trigger powerful eruptions; and, although these eruptions occur far from Earth, they can affect Earth in dramatic ways, including auroral displays. Auroras, the eerie and pretty northern and southern lights, are produced when gases in Earth's upper atmosphere glow from energy delivered by the solar wind.
3. In some regions of the solar surface, the magnetic field does not loop back. High-energy gas from these regions flows outward and produces much of the solar wind.

Solar eruptions, although occurring millions of kilometres away, can eject enormous amounts of charged particles that can be severely disruptive to satellite communications and to TV and cell phone signals on Earth. A radio solar telescope network run by the U.S. Air Force monitors such emissions but does not provide complete real-time coverage. Recently, a low-cost system of spectrometers called the e-CALLISTO network, originally designed by amateur astronomer Christian Monstein, has been set up at locations around the world, including Mongolia, Kazakhstan, Egypt, Indonesia, India, Peru, Ethiopia, and Costa Rica (Figure 5.21). The network monitors the Sun 24 hours a day and can act as an early-warning system for disruptions caused by solar flares. "We wanted 24-hour coverage, but we also wanted to take radio astronomy to countries that could not afford it," said astrophysicist Arnold Benz, who worked with Monstein to distribute the CALLISTO instruments around the world.

You needed the entire range of physical principles presented in this chapter—parallax, Wien's law and the Stefan–Bolzmann law for blackbody radiation, atomic structure, Kirchhoff's laws for the formation of spectra, the Doppler effect, the Zeeman effect—to realize how the Sun's surface temperature and composition are known, and to understand solar activity cycles and their effects on Earth. In the next chapter you will learn how the Sun fits into the context of other stars.



Figure 5.21 An e-CALLISTO spectrometer in Pune, India.

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Visualizing Astronomy 5.3

MAGNETIC SOLAR PHENOMENA

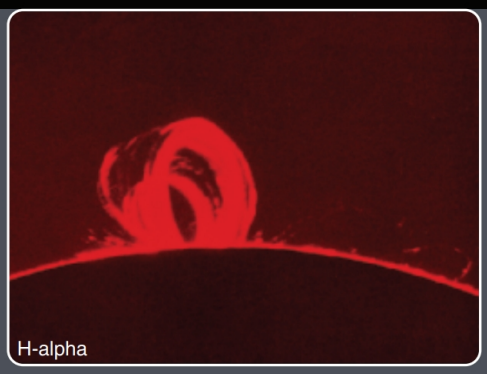
1

Magnetic phenomena in the chromosphere and corona, like magnetic weather, result as constantly changing magnetic fields in the Sun's atmosphere trap ionized gas to produce beautiful arches and powerful outbursts. Some of this solar activity can affect Earth's magnetic field and atmosphere.

This ultraviolet image of the solar surface was made by the NASA TRACE spacecraft. It shows hot gas trapped in magnetic arches extending above active regions. At visual wavelengths, you would see sunspot groups in these active regions.

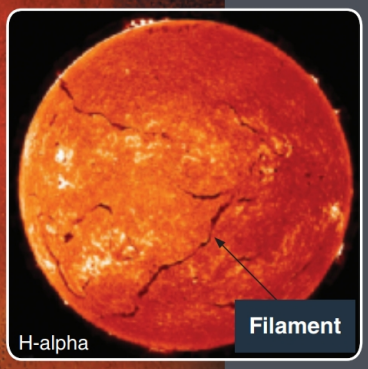
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NASA/TRACE



Sacramento Peak Observatory/NSO/AURA/NSF

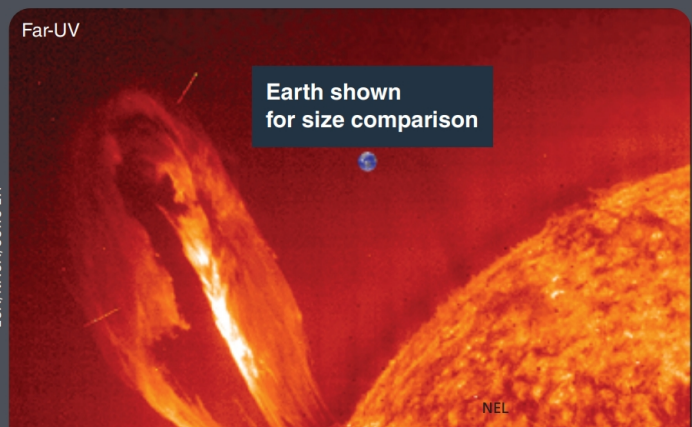
1a A **prominence** is composed of ionized gas trapped in a magnetic arch rising up through the photosphere and chromosphere into the lower corona. Seen during total solar eclipses at the edge of the solar disk, prominences look pink because of emission lines from hydrogen gas. The image above shows the arch shape suggestive of magnetic fields. Seen from above against the Sun's bright surface, prominences form dark **filaments**.



NOAA/SEL/USAF

1b Quiescent prominences may hang in the lower corona for many days, whereas eruptive prominences burst upward in hours. The eruptive prominence below is many Earth diameters in length.

The gas in prominences may be 60 000 to 80 000 K, quite cold compared with the low-density gas in the corona, which may be as hot as a million Kelvin.



ESA/NASA/SOHO EIT

NEL

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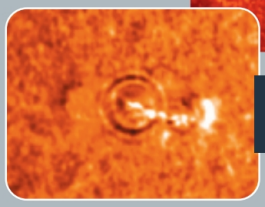
2 Solar **flares** rise to maximum in minutes and decay in an hour. They occur in active regions where oppositely directed magnetic fields meet and cancel each other in what are called **reconnection events**. Energy stored in the magnetic fields is released as short-wavelength photons plus high-energy protons and electrons. X-ray and ultraviolet photons reach Earth in 8 minutes and increase ionization in our upper atmosphere, which can interfere with radio communications. Particles from flares reach Earth hours or days later as gusts in the solar wind, which can distort Earth's magnetic field and disrupt navigation systems. Solar flares can also cause surges in electrical power lines and damage to Earth satellites.



This multiwavelength image shows a sunspot interacting with a neighbouring magnetic field to produce a solar flare.

Hinode JAXA/NASA

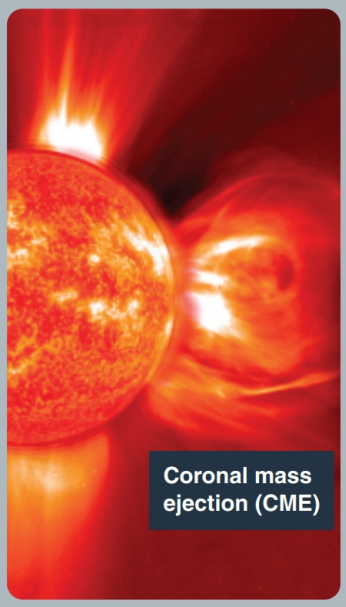
2a At right, waves rush outward at 50 km/s from the site of a solar flare 40 000 times stronger than the 1906 San Francisco earthquake. The biggest solar flares can be a billion times more powerful than a hydrogen bomb.



SOHO/MDI, ESA and NASA

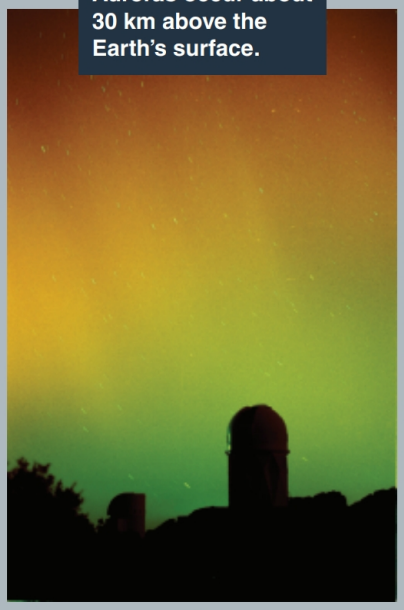
Helioseismology Doppler image

ESA/NASA/SOHO

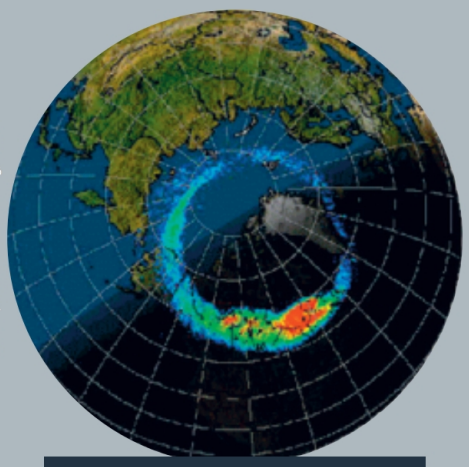


Coronal mass ejection (CME)

Auroras occur about 30 km above the Earth's surface.



Adam Block/NOAO/AURA/NSF



NSSDC, Holzworth and Meng/NASA

Ring of auroras around the north magnetic pole

2b The solar wind, enhanced by eruptions on the Sun, interacts with Earth's magnetic field and can create electrical currents with up to a million megawatts of power. Those currents flowing down into a ring around Earth's magnetic poles excite atoms in Earth's upper atmosphere to emit photons, as shown above. The emission results in glowing clouds and curtains of **auroras**.

2c Magnetic reconnections can release enough energy to blow large amounts of ionized gas outward from the corona in **coronal mass ejections (CMEs)**. If a CME strikes Earth, it can produce especially violent disturbances in Earth's magnetic field.

3 Much of the solar wind comes from **coronal holes**, where the magnetic field does not loop back into the Sun. These open magnetic fields allow ionized gas in the corona to flow away as the solar wind. The dark area in this X-ray image at right is a coronal hole.



SAS/NASA/Yokoh

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HOW DO WE KNOW? 5.1



Confirmation, Confidence, and Consolidation

Science is not always about upending paradigms and dramatically changing the way people view nature. Many experiments and observations are simply carried out to confirm hypotheses that have already been tested. The biologist knows that all worker bees in a hive are sisters, but a careful study of the DNA from different workers further confirms that hypothesis. By repeatedly confirming a hypothesis, scientists build confidence and extend its application. Much of the daily grind of science is confirmation.

Repeated confirmation of hypotheses increases confidence in those hypotheses. Confidence in well-tested scientific principles helps scientists avoid rushing to faulty judgments. For example, claims for perpetual motion machines occasionally crop up in the news, but the world's scientists don't instantly abandon the laws of energy and motion pending an analysis of the latest claim. Because the known laws of energy and motion have been well tested and no perpetual motion machine has ever been successful, scientists know which way to bet.

Confirmation and confidence enable scientists to broaden the application of hypotheses and link them to other phenomena through consolidation. Chemists may understand certain kinds of carbon molecules shaped like rings, but by repeated study they find a carbon molecule shaped like a hollow sphere. To consolidate their findings, they must show that the chemical bonding in the two molecules follows the same rules and that the molecules have certain properties in common.

Scientists' model of the solar magnetic cycle is an example of the scientific process in astronomy. Solar astronomers know that the model has shortcomings, but they work through confirmation and consolidation to better understand how the solar magnetic cycle works and how it is related to cycles in other stars.

The **Big Picture**

We live very close to a star and depend on it for survival. All of our food comes from sunlight that was captured by plants on land or by plankton in the oceans. We either eat those plants directly or eat the animals that feed on those plants. Whether you had salad, seafood, or a cheeseburger for supper last night, you dined on sunlight, thanks to photosynthesis. Almost all of the energy that powers human civilization comes from the Sun through photosynthesis in ancient plants that were buried and converted to coal, oil, and natural gas. New technology is making energy from plant products such as corn, soybeans, and sugar. It is all stored sunlight. Windmills generate electrical power, and the wind blows because of heat from the Sun. Photocells make electricity directly from sunlight. Even our bodies have adapted to use sunlight to manufacture vitamin D.

Our planet is warmed by the Sun, and without that warmth the oceans would be ice and much of the atmosphere would be a coating of frost. Books often refer to the Sun as "our Sun" or "our star." It is ours in the sense that we live beside it and by its light and warmth, but we can hardly say it belongs to us. It is more correct to say that we belong to the Sun.

This chapter has helped you realize how little astronomers would know about the Sun were it not for analyses of its spectrum. Just a bit of spectroscopic ingenuity reveals that the brilliance of the Sun hides a complex atmosphere of hot gases, churned by powerful storms that affect our lives on Earth.

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Review and Discussion Questions

Review Questions

1. How was the distance to the Sun first determined?
2. How is the mass of the Sun determined?
3. Define density. How is the density of the Sun determined?
4. Why is the binding energy of an electron related to the size of its orbit?
5. Explain why ionized calcium can form absorption lines, but ionized hydrogen cannot.
6. Describe two ways an atom can gain energy and become what is called "excited," with one or more electrons moved to higher orbits.
7. Why do different atoms have different lines in their spectra?
8. Why do hot stars look bluer than cool stars?
9. What kind of spectrum does a neon sign produce?
10. If a nebula contains mostly hydrogen excited to emit photons, what kind of spectrum would you expect it to produce?
11. Why does the Doppler effect detect only radial velocity?
12. How are astronomers able to explore the layers of the Sun below the photosphere?
13. What evidence can you give that sunspots and prominences are magnetic?
14. How can solar flares affect Earth?

Discussion Questions

1. In what ways is the model of an atom a scientific model?
2. Explain why the presence of spectral lines of a given element in the solar spectrum tells you that element is present in the Sun, but the absence of the lines would not necessarily mean the element is absent from the Sun.
3. What observations would you make if you were ordered to set up a system that could warn astronauts in orbit of dangerous solar flares? (Such a warning system actually exists.)

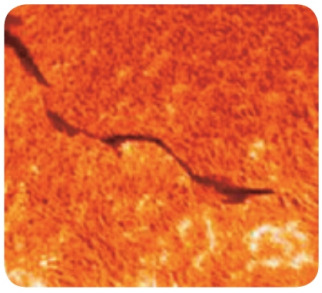
Learning to Look

1. The glowing gas cloud shown in the next column contains mostly hydrogen excited to emit photons. What kind of spectrum would you expect this gas cloud to produce?

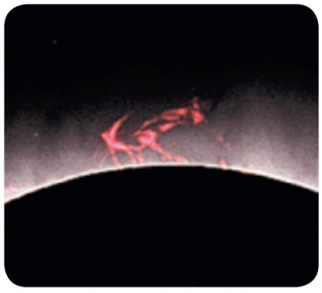


T. Rector, University of Alaska and WIYN, NURO/AURA/NSF

2. If the gas cloud in the image crosses in front of a star, and the gas cloud and star have different radial velocities, what would the combined spectrum of the gas cloud and the star look like?
3. The two images here show two solar phenomena. What are they, and how are they related? How do they differ?



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STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *The Sun: The Closest Star.*

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
- Interactive Quizzing
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PART TWO

6 The Family of Stars



European Southern Observatory

CHAPTER OUTLINE

6.1 Star Distances
6.2 Apparent Brightness, Intrinsic Brightness, and Luminosity
6.3 Star Temperatures
6.4 Star Sizes
6.5 Star Masses: Binary Stars
6.6 Typical Stars

GUIDEPOST

To discover the properties of stars, astronomers use telescopes and instruments such as photometers, cameras, and spectrographs in clever ways to learn the secrets hidden in starlight. The result is a family portrait of the stars. Knowing the distances to stars is the key to knowing most of their other properties, but measuring those distances is very difficult.

In this chapter you will find answers to five important questions about stars:

- How far away are the stars?
- How much energy do stars emit?
- How do spectra of stars allow determination of their temperatures?
- How big are stars?
- How much mass do stars contain?

With this chapter, you leave the Sun behind and begin your study of the billions of stars that dot the sky. In a sense, stars are the basic building blocks of the universe. If you hope to understand what the universe is, what our Sun is, what our Earth is, and what we are, you need to understand stars. Once you know how to find the basic properties of stars, you will be ready to trace the history of the stars from birth to death, a story that begins in the next chapter.

William Shakespeare compared love to a star that can be seen easily and even used for guidance, but whose real nature is utterly unknown.

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An image of the Jewel Box open star cluster, NGC 4755, located in the constellation Crux. Several blue supergiant stars and one red supergiant can be seen. The cluster is about 6400 light-years away. Characteristics of the stars in it provide evidence that the cluster is very young, only 16 million years old.

The night is even more richly colored than the day. . . . If only one pays attention to it, one sees that certain stars are citron yellow, while others have a pink glow or a green, blue and forget-me-not brilliance. And without my expiating on this theme, it should be clear that putting little white dots on a blue-black surface is not enough.

Vincent van Gogh, painter

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He lived at about the same time as Galileo and had no idea what stars actually are. By studying the history of the universe, the origin of Earth, and the nature of our human existence, you will learn something that people in Shakespeare's time did not know—the real nature of the stars. Unfortunately, it is quite difficult to find out what a star is like. When you look at a star, even through a telescope, you see only a point of light. Real understanding of stars requires careful analysis of starlight. This chapter concentrates on five goals: knowing how far away stars are, how much energy they emit, what their surface temperatures are, how big they are, and how much mass they contain. By the time you finish this chapter, you will know the family of stars well.

6.1 Star Distances

The first goal for this chapter is to find out how far away stars are from Earth. Distance is one of the most important and certainly the most difficult measurement in astronomy, and astronomers have devised many different ways to determine the distances to stars. Stellar distances within our neighbourhood of the Milky Way galaxy utilize a simple geometric method called stellar parallax that is much like the technique surveyors use to measure the distance across a river. First, we will use this method to determine the distance across the Ottawa River from the Canadian Museum of History in Gatineau, Quebec, to the Parliamentary Library on Parliament Hill in Ottawa, Ontario. Then we apply this method to measuring stellar distances.

The Surveyor's Triangulation Method

To measure the distance across the Ottawa River, surveyors begin by driving two stakes into the ground parallel to the shoreline just outside the Museum, as shown in Figure 6.1. The distance between the stakes is called the *baseline*. Using their instruments, the surveyors sight the Library from each end of the baseline and measure the angle between the sightline and the baseline on their side of the river. Knowing two angles of this large triangle and the length of the baseline side between them, the surveyors can find the distance across the river to the Library by simple trigonometry. For example, if the baseline is 200 m and the interior angles at apexes A and B are 81.0° and 76.4°, respectively, they can calculate that the distance from the baseline to the Library is 500 m.

stellar parallax (*p*) The small apparent shift in position of a nearby star relative to distant background objects due to Earth's orbital motion.

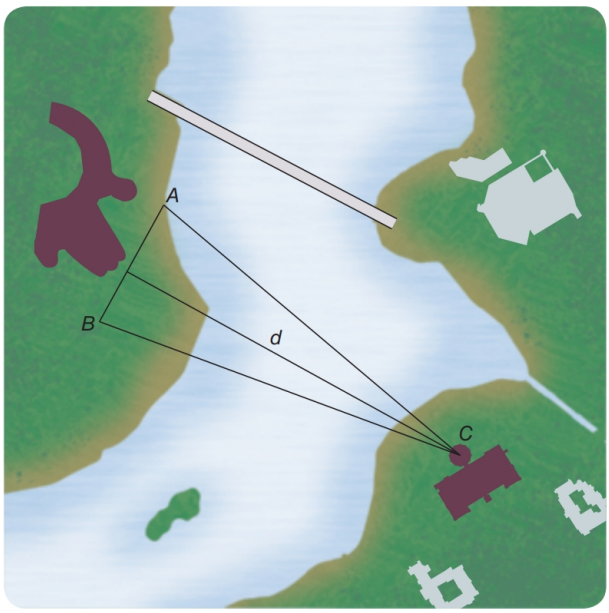


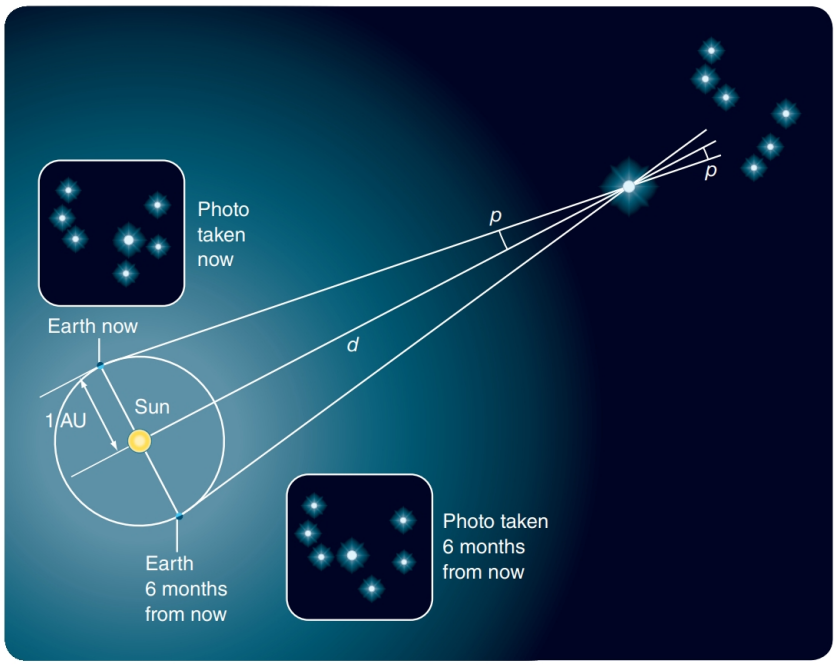
Figure 6.1 The distance across a river (*d*) can be determined by measuring the length of a baseline along with the angles at vertices *A* and *B*. A simple trigonometric calculation yields the value of *d*.

The Astronomer's Triangulation Method

You can now extend this method to find the distance to a star. Astronomers use a very long baseline, the diameter of Earth's orbit (see Figure 6.2). If you take a photograph of a nearby star and then wait six months, Earth will have moved halfway around its orbit. You can then take another photograph of the star from that slightly different location in space. When you examine the photographs, you will discover that the star is not in exactly the same place in the two photographs. As mentioned above, this method is called stellar parallax. Recall from Chapter 3 that parallax is the term that refers to the common experience of an apparent shift in the position of a foreground object due to a change in the location of the observer's viewpoint.

Because the stars are so distant, their parallaxes are very small angles, usually expressed in arc seconds. The quantity that astronomers call **stellar parallax (*p*)** is conventionally defined as half the total shift of the star (shown in Figure 6.2); in other words, the shift seen across a baseline of 1 AU rather than 2 AU. Astronomers measure the parallax, and surveyors measure the angles at the ends of the baseline, but both measurements tell the same

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Figure 6.2 You can measure the parallax of a nearby star by photographing it from two points along Earth's orbit. For example, you might photograph it now and again in six months. Half of the star's total change in position from one photograph to the other is defined as its stellar parallax, *p*.

thing—the shape and size of the triangle and therefore the distance to the object in question. (Refer to **Parallax and Distance** in the Math Reference Cards.)

Measuring the parallax *p* is very difficult because it is such a small angle. The nearest star, Alpha Centauri, has a parallax of only 0.76 arc seconds, and more distant stars have even smaller parallaxes. To see how small these angles are, imagine a dime about 3 kilometres away from you. That dime covers an angle of about 1 arc second. Stellar parallaxes are so small that the first successful measurement of one did not happen until 1838, more than 200 years after the invention of the telescope.

The distances to the stars are so large that it is not convenient to use kilometres or astronomical units. For such large distances there are two main measurement units: light-years and parsecs. In this textbook we have chosen to use light-years because conceptually it is the simpler of the two options. A light-year (ly) is merely the distance light travels in one year. If we state the distance to the star Rigel in the constellation Orion is 772.5 ly, we mean that the light we are seeing today left Rigel 772.5 years ago. When you look at the sky at night you are actually looking back in time! Astronomers also measure distances to stars via parallax and therefore use the unit of distance called a **parsec (pc)**. The word *parsec* was created by combining *parallax* and arc *second*. One parsec equals the distance to an imaginary star that has a parallax of 1 arc second. A parsec is 206 265 AU, which equals roughly 3.26 ly. In the following chapters we have tried to be consistent in our use of light-years as the unit of measurement; there may be a few instances when parsecs have been used as convenience and custom dictate.

The blurring caused by Earth's atmosphere makes star images appear to be about 1 arc second in diameter, and that makes it difficult to measure parallax. Even if you average together many observations made from Earth's surface, you cannot measure parallax with an uncertainty smaller than about 0.002 arc seconds. If you measure a parallax of 0.006 arc seconds from an observatory on the ground, your uncertainty will be about 30 percent. If you consider, as astronomers generally do, that 30 percent is the maximum acceptable level of uncertainty, then ground-based astronomers cannot accurately measure parallaxes that are smaller than about 0.006 arc seconds. That parallax corresponds to a distance of about 550 ly.

Improvements in stellar parallax measurements can be made by utilizing satellites orbiting above Earth's atmosphere. In 1989, the European Space Agency (ESA) launched the satellite *Hipparcos* to measure stellar parallaxes, and thus distances, from above the blurring effects of Earth's atmosphere. The *Hipparcos* telescope observed for four years, resulting in two parallax catalogues in 1997. One catalogue contains 120 000 stars with parallaxes 20 times more accurate than ground-based measurements. The other catalogue contains over a million stars with parallaxes as accurate as ground-based parallaxes. Knowing accurate distances from the *Hipparcos* observations has given astronomers new insights into the nature of stars.

In late 2013 the ESA launched the *Gaia* spacecraft to measure the positions and distances of stars in our part of the Milky Way galaxy with great precision. *Gaia*'s goal is to observe about 1 billion stars and other bodies having an apparent visual magnitude of +20. The data should produce the first accurate three-dimensional map of our galaxy. The complete *Gaia* catalogue is expected to be available in 2022 or 2023.

You will learn about other methods of determining extragalactic objects later in this book.

parsec (pc) The distance to a hypothetical star whose parallax is 1 arc second.

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6.2 Apparent Brightness, Intrinsic Brightness, and Luminosity

When you look at the night sky it's obvious that some stars appear brighter than others. In Chapter 2 you learned about the magnitude scale that refers to apparent stellar brightness. However, the scale of apparent magnitudes tells you only how bright stars appear to you on Earth. To know the true nature of a star you must know its **intrinsic brightness**, a measure of the amount of light the star produces. An intrinsically very bright star might appear faint if it is far away. Consequently, to know the intrinsic brightness of a star, you must take into account its distance.

Brightness and Distance

When you look at a bright light, your eyes respond to the visual-wavelength energy falling on your retinas, which tells you how bright the object appears. Brightness is related to the flux of energy entering your eye. Astronomers and physicists define **flux** as the energy in joules (J) per second falling on 1 square metre. Recall that a joule is about the amount of energy released when an apple falls from a table onto the floor. A flux of 1 joule per second is also known as 1 watt. The wattage of a light bulb tells you its *intrinsic* brightness. Compare that with the *apparent* brightness of a light bulb, which depends on its distance from you.

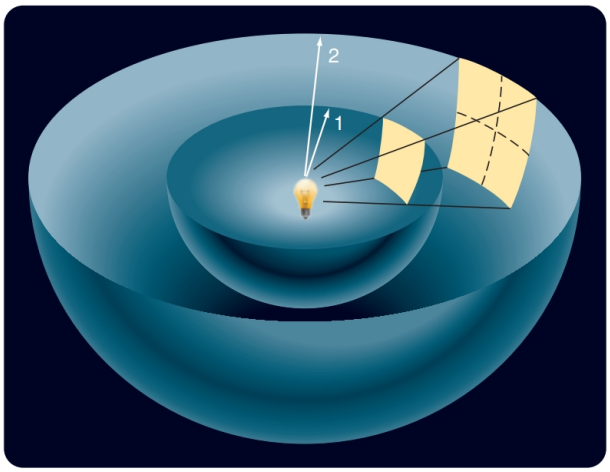
If you placed a screen 1 metre square near a light bulb, a certain amount of flux would fall on the screen. If you moved the screen twice as far from the bulb, the light that previously fell on the screen would be spread to cover an area four times larger, and the screen would receive only one-fourth as much light. If you tripled the distance to the screen, it would receive only one-ninth as much light. This demonstrates that the flux you receive from a light source is inversely proportional to the square of the distance to the source. This is known as the inverse square relation (see Figure 6.3). You first encountered the inverse square relation in Chapter 3, where it was applied to the strength of gravity.

intrinsic brightness A measure of the amount of light a star produces.

flux A measure of the flow of energy out of a surface; usually applied to light.

absolute visual magnitude (M_V) Intrinsic brightness of a star. The apparent visual magnitude the star would have if it were 33 ly away.

Now you can understand how the apparent brightness of a star depends on its distance. If astronomers know the apparent brightness of a star and its distance from Earth, they can use the inverse square law to correct for distance and find the intrinsic brightness of the star.



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Figure 6.3 The inverse square relation. A light source is surrounded by imaginary spheres with radii of 1 unit and 2 units. The light falling on an area of 1 m^2 on the inner sphere spreads to illuminate an area of 4 m^2 on the outer sphere. Thus, the brightness of the light source is inversely proportional to the square of the distance.

Absolute Visual Magnitude

If all the stars were the same distance away, you could compare one with another and decide which was intrinsically brighter or fainter. Of course, the stars are scattered at different distances, and you can't move them around to line them up for comparison. If, however, you know the distance to a star by using the parallax method described earlier in this chapter, you can use the inverse square relation to calculate the brightness the star would have at some standard distance. Astronomers use 33 ly (10 pc) as the standard distance and refer to the intrinsic brightness of the star as its **absolute visual magnitude (M_V)**, which is the apparent visual magnitude that star would have if it were 33 ly away. The subscript V tells you it is a visual magnitude, referring only to the wavelengths of light your eye can see. Other magnitude systems are based on other parts of the electromagnetic spectrum, such as infrared and ultraviolet radiation.

The Sun's absolute magnitude is easy to calculate because its distance and apparent magnitude are well known. The absolute visual magnitude of the Sun is about 4.8. In other words, if the Sun were only 33 ly from Earth (not a great distance in astronomy), it would have an apparent magnitude of 4.8 and look no brighter to your eye than the faintest star in the handle of the Little Dipper. (Refer to **Absolute Magnitude and Distance** in the Math Reference Cards.)

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This path to find the distance to stars has led you to absolute magnitude, a measure of the intrinsic brightness of the stars.

Luminosity

The second goal for this chapter is to find out how much energy the stars emit. With the absolute magnitudes of the stars in hand, you can now compare stars using our Sun as a standard. The intrinsically brightest stars have absolute magnitudes of about −8. If such a star were 33 ly away from Earth, it would seem nearly as bright as the Moon. Such stars emit over 100 000 times more visible light than the Sun.

Absolute visual magnitude refers to visible light, but you want to know the total output including all types of radiation covering the entire electromagnetic spectrum. Hot stars emit a great deal of ultraviolet radiation that you can't see, and cool stars emit plenty of infrared radiation. To add in the energy you can't see, astronomers make a mathematical correction that depends on the temperature of the star. With that correction, astronomers can find the total electromagnetic energy output of a star, which they refer to as its **luminosity (*L*)**.

Astronomers know the luminosity of the Sun because they can send satellites above Earth's atmosphere and measure the amount of energy arriving from the Sun, adding up radiation of every wavelength, including the types blocked by the atmosphere. Of course, they also know the distance from Earth to the Sun very accurately, which is necessary to calculate luminosity. The luminosity of the Sun is about 4×10^{26} watts (joules per second).

You can express a star's luminosity in two ways. For example, you can say that the star Capella (Alpha Aurigae) is 100 times more luminous than the Sun. You can also express this in real energy units by multiplying by the luminosity of the Sun. Consequently the luminosity of Capella is 4×10^{28} watts.

When you look at the night sky, the stars look much the same, yet your study of distances and luminosities reveals an astonishing fact. Some stars are almost a million times more luminous than the Sun, and some are almost a million times less luminous. Clearly, the family of stars is filled with interesting characters.

6.3 Star Temperatures

The third goal for this chapter is to learn about the temperatures of stars. The surprising fact is that stellar spectral lines can be used as a sensitive star thermometer.

From the discussion of blackbody radiation in Chapter 5, you know that temperatures of stars can be estimated from their colour: red stars are cool, and blue stars are hot. The relative strengths of various spectral lines, however, give much greater accuracy in measuring star temperatures. Recall from Chapter 5 that, for stars, the term *surface* refers to the photosphere, which is the limit of our vision into the star from outside, but it is not an actual solid surface. Stars typically have surface temperatures of a few thousand or tens of thousands of degrees Kelvin. As you will discover in Chapter 7, the centres of stars are much hotter than their surfaces—many millions of degrees hotter—but the spectra tell only about the outer layers from which the light you see departed.

As you learned in Chapter 5, hydrogen Balmer absorption lines are produced by hydrogen atoms with electrons initially in the second energy level. The strength of these spectral lines can be used to gauge the temperature of a star because scientists know the following details from lab experiments with gases and radiation, and also from theoretical calculations:

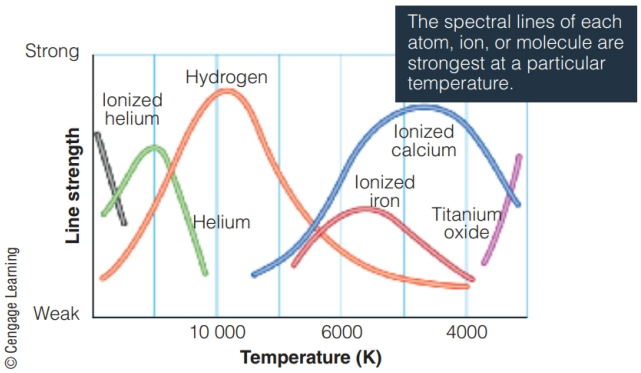
- If the surface of a star is as cool as the Sun or cooler, there are relatively few violent collisions between atoms to excite the electrons, and most atoms will have their electrons in the ground (lowest) state. These atoms can't absorb photons in the Balmer series. As a result, you can expect to find weak hydrogen Balmer absorption lines in the spectra of very cool stars.
- In the surface layers of stars hotter than about 20 000 K, there are many violent collisions between atoms, exciting electrons to high energy levels or knocking the electrons completely out of most atoms, and so they become ionized. In this situation, few hydrogen atoms will have electrons in the second energy level to form Balmer absorption lines. As a result, you can also find weak hydrogen Balmer absorption lines in the spectra of very hot stars.
- At an intermediate temperature, roughly 10 000 K, the collisions have the correct amount of energy to excite large numbers of electrons into the second energy level. With many atoms excited to the second level, the gas absorbs Balmer-wavelength photons well and thus produces strong hydrogen Balmer lines.

The strength of the hydrogen Balmer lines therefore depends on the temperature of the star's surface layers. Both hot and cool stars have weak Balmer lines, but medium-temperature stars have strong Balmer lines.

Figure 6.4 shows the relationship between gas temperature and strength of spectral

luminosity (*L*) The total amount of energy a star radiates per second at all wavelengths.

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Figure 6.4 The strength of spectral lines can tell you the temperature of a star. Using the lines of several atoms or molecules gives you the most accurate results.

lines for hydrogen and other substances. As you can see in this figure, each type of atom or molecule produces spectral lines that are weak at high and low temperatures and strong at some intermediate temperature, although the temperature at which the lines reach maximum strength is different for each type of atom or molecule. Theoretical calculations of the type first made by Cecilia Payne (discussed in Chapter 5) can predict just how strong various spectral lines should be for stars of different temperatures. Astronomers can, therefore, determine a star's temperature by comparing the strengths of its spectral lines with the predicted strengths.

From stellar spectra, astronomers have found that the hottest stars have surface temperatures above 40 000 K, and the coolest are about 2500 K. Compare these with the surface temperature of the Sun, which is about 5800 K.

spectral class A star's position in the temperature classification system O, B, A, F, G, K, M, based on the appearance of the star's spectrum.

Temperature Spectral Classification

You have seen that the strengths of spectral lines depend on the surface (photosphere) temperature of the star. From this you can predict that all stars of a given temperature should have similar spectra. Learning to recognize the pattern of spectral lines produced in the atmospheres of stars of different temperatures means there is no need to do a full analysis every time each type of spectrum is encountered. Time can be saved by classifying stellar spectra rather than analyzing each spectrum individually. Astronomers classify stars by the lines and bands in their spectra, as shown in Table 6.1. For example, if a star has weak Balmer lines and lines of ionized helium, it must be classified as an O star.

The star classification system now used by astronomers was devised at Harvard University during the 1890s and 1990s. The origin of this classification system is an interesting one. The Harvard College Observatory was funded in the late 1800s through a private grant that the director, Edward Pickering, used to hire mostly women (graduates in physics or astronomy) to classify stellar spectra. One such "computer," as they were called, was Williamina Fleming, who classified more than 10 000 stars using the scheme for identifying the spectral lines of hydrogen. Later, another "computer," Annie Jump Cannon, extended Fleming's work and developed the system described on the previous picture, eventually classifying more than 400 000 stars! The spectra were first classified in groups labelled A through Q, but some groups were later dropped, merged with others, or reordered. The final classification includes seven main **spectral classes** or types that are still used today: O, B, A, F, G, K, M. This set of star types, called the

Table 6.1 | Spectral Classes

Spectral Class	Approximate Temperature (K)	Hydrogen Balmer Lines	Other Spectral Features	Unaided Eye Example
O	40 000	Weak	Ionized helium	Meissa (O8)
B	20 000	Medium	Neutral helium	Achernar (B3)
A	10 000	Strong	Ionized calcium weak	Sirius (A1)
F	7500	Medium	Ionized calcium weak	Canopus (F0)
G	5500	Weak	Ionized calcium medium	Sun (G2)
K	4500	Very weak	Ionized calcium strong	Arcturus (K2)
M	3000	Very weak	TiO strong	Betelgeuse (M2)

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spectral sequence, is important because it is a temperature sequence. The O stars are the hottest, and the temperature continues to decrease down to the M stars, the coolest. For further precision, astronomers divide each spectral class into 10 subclasses. For example, spectral class A consists of the subclasses A0, A1, A2 … A8, A9. Next come F0, F1, F2, and so on. These finer divisions define a star's temperature to a precision of about 5 percent. The Sun, for example, is not just a G star, but a G2 star, with a temperature of 5800 K. Generations of astronomy students have remembered the spectral sequence by using mnemonics such as "Oh, Be A Fine Girl/Guy, Kiss Me," or "Oh Boy, An F Grade Kills Me." You can make up your own phrase if you wish.

Figure 6.5 shows colour images of 13 stellar spectra ranging from the hottest at the top to the coolest at the bottom. Notice how spectral features change gradually from hot to cool stars. Although these spectra are attractive, astronomers rarely work with spectra as colour images. Rather, they display spectra as graphs of intensity versus wavelength, with dark absorption lines as dips in the graph in Figure 6.6. Such graphs show more detail than photographs. Notice also that the overall curves are similar to blackbody curves. The wavelength of maximum is in the infrared for the coolest stars and in the ultraviolet for the hottest stars. Compare Figures 6.5 and 6.6, and notice how the strength of spectral lines depends on temperature, as indicated in the previous discussion regarding Figure 6.4. It is fairly straightforward to determine a star's temperature from the details of its spectrum.

spectral sequence The arrangement of spectral classes (O, B, A, F, G, K, M) ranging from hot to cool.

L dwarf, T dwarf Spectral classes of brown dwarf stars with lower surface temperatures and luminosities than M dwarfs.

brown dwarf A very cool, low-luminosity star whose mass is not sufficient to ignite nuclear fusion.

The study of spectral types is more than a century old, but astronomers continue to discover and define new types. The **L dwarfs,** found in 1998, are cooler and fainter than M stars. They are understood to be objects smaller than stars but larger than planets; they are called **brown dwarfs** and you will learn more about them in a later chapter. The spectra of M stars contain bands produced

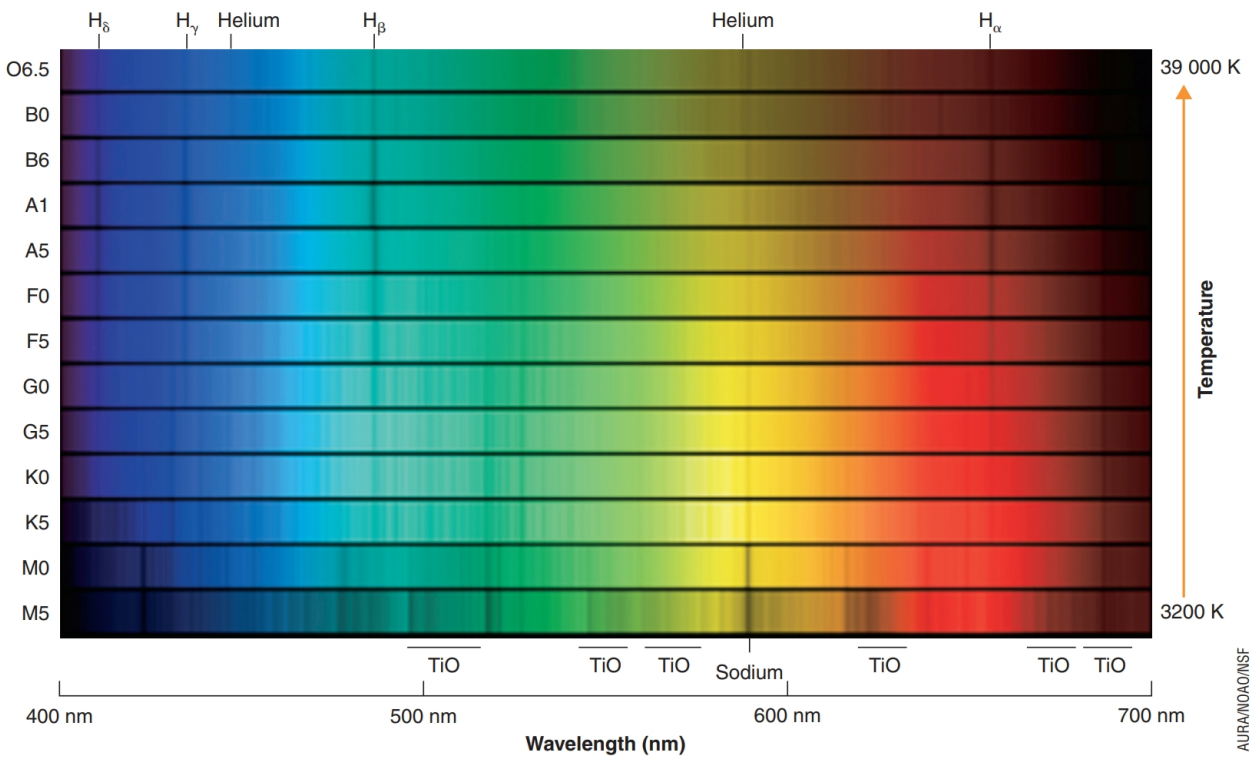


Figure 6.5 These spectra show stars from hot O stars at top to cool M stars at bottom. The hydrogen Balmer lines are strongest for about type A0, but the two closely spaced lines of sodium in the yellow are strongest for very cool stars. Helium lines appear only in the spectra of the hottest stars. Notice that the helium line visible in the top spectrum has nearly—but not exactly—the same wavelength as the sodium lines visible in cooler stars. Bands produced by the molecule titanium oxide are strong in the spectra of the coolest stars.

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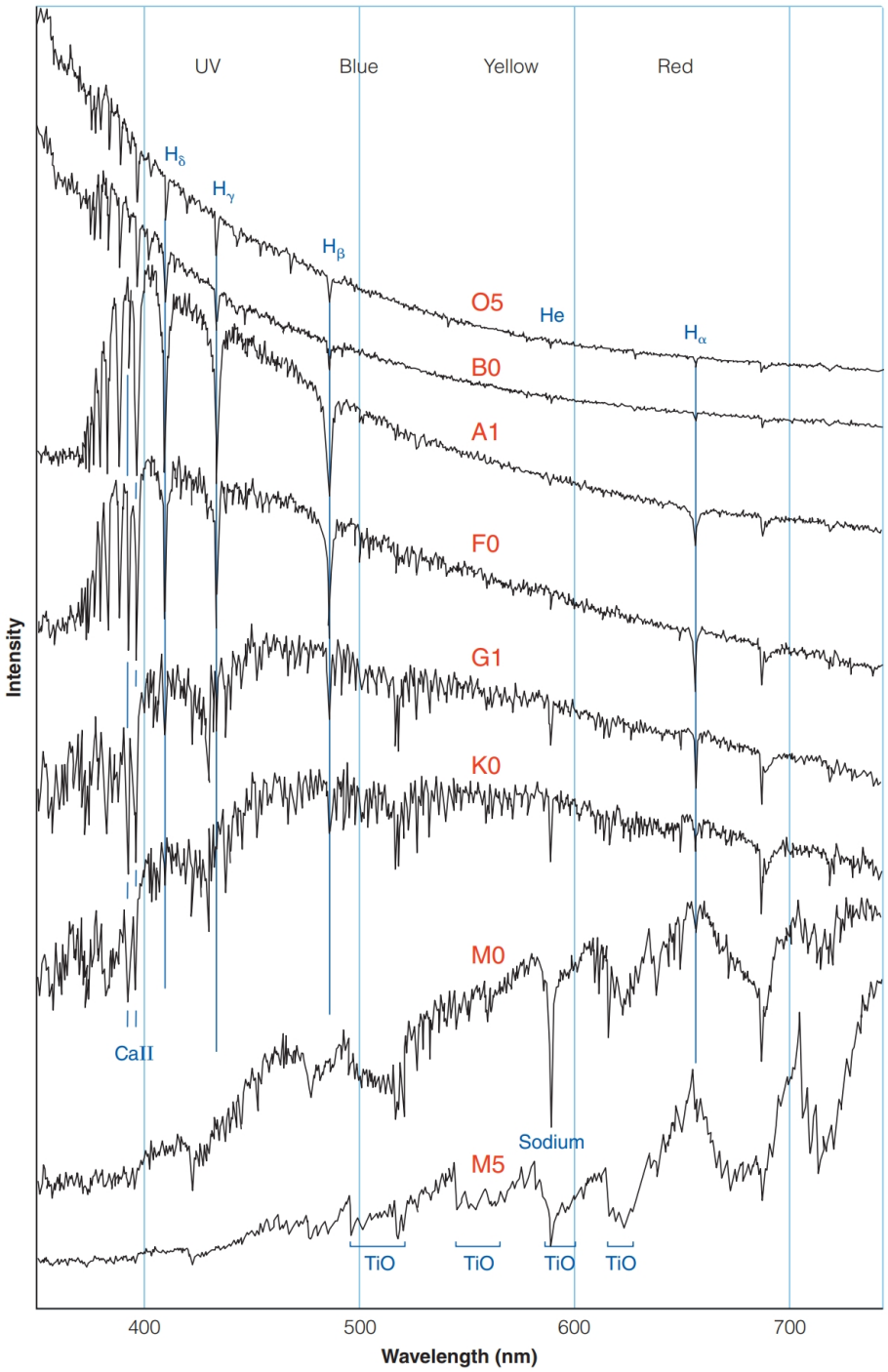


Figure 6.6 Modern digital spectra show how stellar spectra depend on spectral class. Here spectra are represented by graphs of intensity versus wavelength, and dark absorption lines appear as sharp dips in intensity. Hydrogen Balmer lines are strongest about A0, while lines caused by ionized calcium (Ca II) are strong in K stars. Bands produced by molecules such as TiO (titanium oxide) are strong in the coolest stars. Compare these spectra with Figures 6.4 and 6.5.

Y dwarf A substellar object with temperature below 500 K, having inferred properties intermediate between brown dwarfs and Jovian planets.

by metal oxides such as titanium oxide (TiO), but L dwarf spectra contain bands produced by molecules such as iron hydride (FeH). The **T dwarfs** are an even cooler and fainter type of brown dwarf than L dwarfs. Their spectra show absorption by methane (CH_4) and water vapour. In 2011, astronomers using infrared space telescopes, large ground-based telescopes, and highly sensitive infrared detectors discovered a class of objects with temperatures below 500 K that are labelled **Y dwarfs**.

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6.4 Star Sizes

The fourth goal for this chapter is to learn about the sizes of stars. Do they all have the same diameter as the Sun, or are some larger and some smaller? You certainly can't see their sizes through a telescope; the images of the stars are much too small for you to resolve their disks and measure their diameters. There is a way, however, to find out how big stars really are.

Luminosity, Temperature, and Diameter

The luminosity of a glowing object like a star is determined by its temperature (Stefan–Boltzmann law, Chapter 5) and its surface area. For example, you can eat dinner by candlelight because the candle flame has a small surface area, and, although it is very hot, it cannot radiate much heat because it is small; it has a low luminosity. However, if the candle flame were 4 m tall, it would have a very large surface area from which to radiate, and, although it might be the same temperature as a normal candle flame, its luminosity would drive you from the table.

In a similar way, a star's luminosity is proportional to its surface area. A hot star may not be very luminous if it has a small surface area, but it could be highly luminous if it were larger. Even a cool star could be luminous if it had a large surface area. You can use stellar luminosities to determine the diameters of stars if you can separate the effects of temperature and surface area. Thus, the luminosity of a star depends on two things: its size and its temperature. (Refer to **Luminosity, Radius, and Temperature** in the Math Reference Cards.)

The **Hertzsprung–Russell (H–R) diagram** is named after its originators, Ejnar Hertzsprung of the Netherlands and Henry Norris Russell of the United States, who independently thought of creating such a diagram. It is a graph that separates the effects of temperature and surface area on stellar luminosities and enables astronomers to sort the stars according to their diameters.

Before discussing the details of the H–R diagram, let's look at a similar diagram you might use to compare automobiles. You can plot a diagram such as Figure 6.7 to show horsepower versus mass for various makes of cars. In so doing, you will find that in general the more massive a car, the more horsepower it has. Most cars fall somewhere along the normal sequence of cars running from heavy, high-powered cars at the top left of the central part of the plot to light, low-powered models at the bottom right. You might call this the main sequence of cars. Some cars, however, have much more horsepower than normal for their mass—the sport or racing models—and the economy models have less power than normal for cars of the same mass. Just as this diagram helps you understand the different kinds of autos, so the H–R diagram can help you understand different kinds of stars.

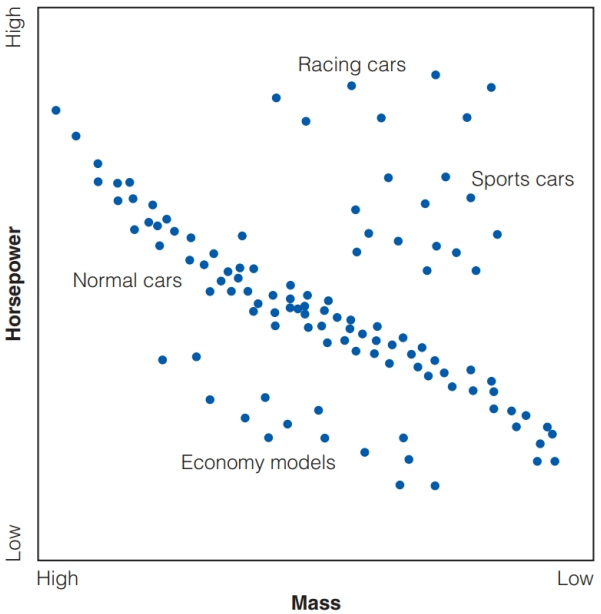


Figure 6.7 Analyzing automobiles by plotting horsepower versus mass reveals relationships among various models; most would be somewhere along the "main sequence" of normal cars.

An H–R diagram, shown in Figure 6.8, has luminosity on the vertical axis and temperature on the horizontal axis. Because the range of numbers on both axes is so large, luminosity and temperature are plotted using a logarithmic scale. Note that the vertical luminosity axis is actually a ratio of luminosities. A star is represented by a point on the graph that tells you its luminosity and temperature. Note that in astronomy the symbol $\odot$ refers to the Sun. Thus $L_\odot$ refers to the luminosity of the Sun, $T_\odot$ refers to the temperature of the Sun, and so on. The H–R diagram in Figure 6.8 also contains a scale of spectral types across the top. The spectral type of a star is determined by its temperature, so you can use either spectral type or temperature as the horizontal axis of an H–R diagram.

Astronomers use H–R diagrams so often that they usually skip the words "the point that represents the star." Rather, they will say that a star is located in a certain place in the diagram. Of course, they mean the point that represents the luminosity and temperature of the star, not the star itself. The location of a star in the H–R diagram has nothing

Hertzsprung–Russell (H–R) diagram A plot of the intrinsic brightness versus the surface temperature of stars. It separates the effects of temperature and surface area on stellar luminosity.

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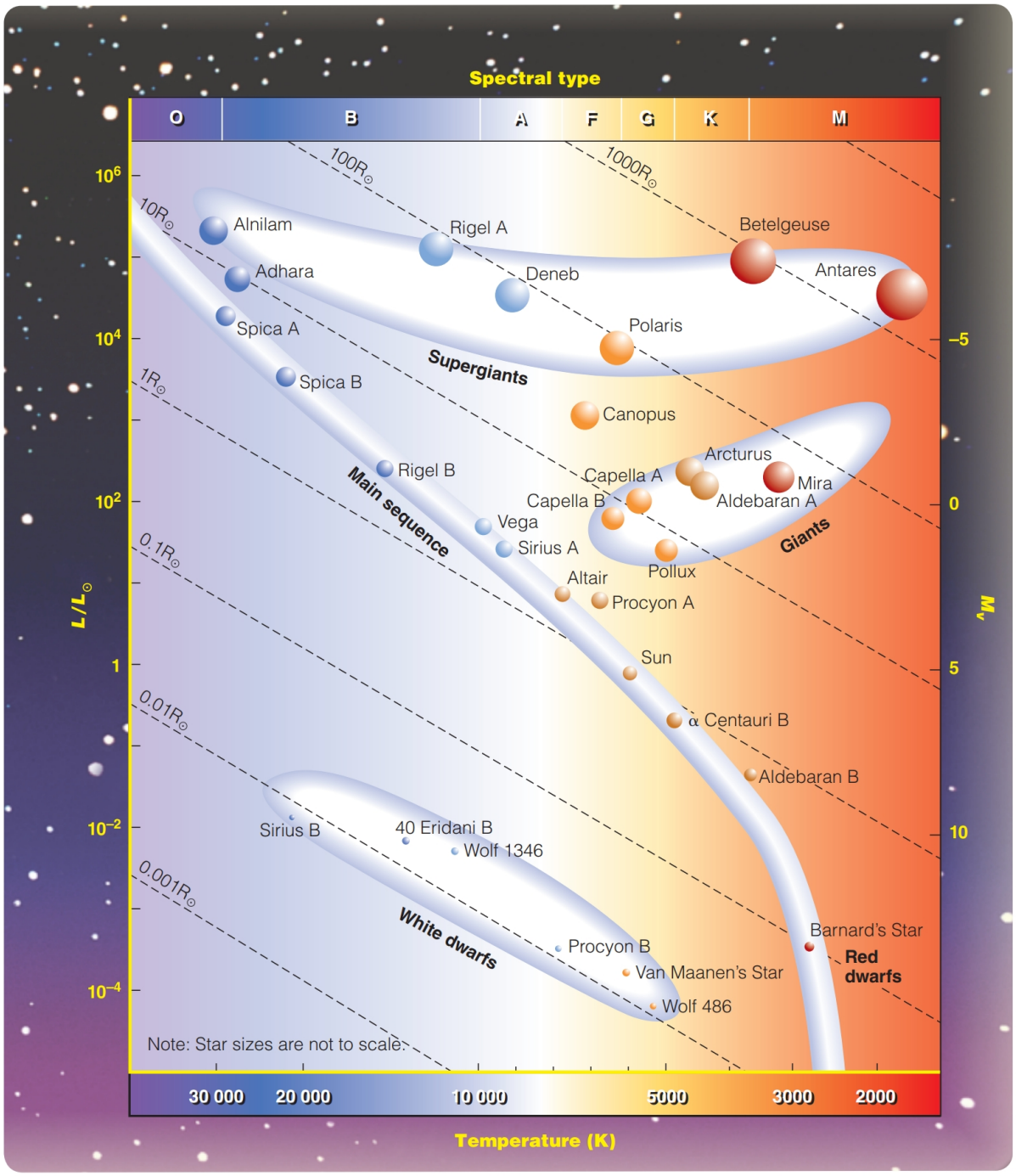


Figure 6.8 An H–R diagram showing the luminosity and temperature of many well-known stars. The dashed lines are lines of constant radius. The star sizes on this diagram are not to scale. (Individual stars that orbit each other are designated A and B, as in Spica A and Spica B.)

to do with the location of the star in space. Furthermore, a star may move within the H–R diagram as it ages and its luminosity and temperature change, but such motion in the diagram has nothing to do with the star's motion in space.

In an H–R diagram, the location of a point representing a star tells you a great deal about the star. Points near the top of the diagram represent very luminous stars, and points near the bottom represent very-low-luminosity stars. Also, points near the right edge of the diagram

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represent very cool stars, and points near the left edge of the diagram represent very hot stars. Notice in Figure 6.8 how the artist has used colour to represent temperature. Cool stars are red, and hot stars are blue.

The **main sequence** is the region of the H–R diagram running from upper left to lower right. It includes roughly 90 percent of all normal stars, represented by a curved line with dots for stars plotted along it in Figure 6.8. As you might expect, the hot main-sequence stars are more luminous than the cool main-sequence stars. Look again at the classification diagram for cars in Figure 6.7. Vehicles not on the car main sequence have different kinds of engines than main-sequence cars. In Chapter 7 you will find that stars not on the main sequence have different nuclear reactions as their power sources than do main-sequence stars. In addition to temperature, size is important in determining the luminosity of a star. Notice in the H–R diagram that some cool stars lie above the main sequence. Although they are cool, they are luminous, and that must mean they are larger—have more surface area—than main-sequence stars of the same temperature. These are called **giant** stars, and they are roughly 10 to 100 times larger than the Sun. The **supergiant** stars at the top of the H–R diagram are as large as 1000 times the Sun's diameter. In contrast, **red dwarfs** at the lower end of the main sequence are not only cool but also small, giving them low luminosities.

At the bottom of the H–R diagram are the "economy models," stars that are very low in luminosity because they are very small. The **white dwarfs** lie in the lower left of the H–R diagram, and although some white dwarfs are among the hottest stars known, they are so small they have very little surface area from which to radiate, and that limits them to low luminosities.

A simple calculation can be made to draw precise lines of constant radius across the H–R diagram based on the luminosities and temperatures at each point as shown in Figure 6.8. For example, locate the line labelled 1 $R_\odot$ (1 solar radius) and notice that it passes through the point representing the Sun. Any star whose point is located along this line has a radius equal to the Sun's radius. Notice also that the lines of constant radius slope downward to the right, because cooler stars are always fainter than hotter stars of the same size, following the Stefan–Boltzmann law. These lines of constant radius show dramatically that the supergiants and giants are much larger than the Sun. In contrast, white dwarf stars fall near the line labelled 0.01 $R_\odot$. They all have about the same radius—approximately the size of Earth!

Notice the great range of sizes among stars. The largest stars are 100 000 times larger than the tiny white dwarfs. If the Sun were a tennis ball, the white dwarfs would be grains of sand, and the largest supergiant stars would be as big as football fields.

Luminosity Spectral Classification

You might find it interesting to learn that a star's spectrum also contains clues as to whether it is a main-sequence star, a giant, or a supergiant. The larger a star is, the less dense its atmosphere is. The widths of spectral lines are partially determined by the density of the gas. If the atoms collide often in a dense gas, their energy levels become distorted, and the spectral lines are broadened. For example, in the spectrum of a main-sequence star, the hydrogen Balmer lines are broad because the star's atmosphere is dense and the hydrogen atoms collide often. In the spectrum of a giant star, the lines are narrower (Figure 6.9), because the giant star's atmosphere is less dense and the hydrogen atoms collide less often. In the spectrum of a supergiant star, the Balmer lines are very narrow.

main sequence The region of the H–R diagram running from upper left to lower right, which includes roughly 90 percent of all stars generating energy by nuclear fusion.

giant A large, cool, highly luminous star in the upper right of the H–R diagram, typically 10 to 100 times the diameter of the Sun.

supergiant An exceptionally luminous star whose diameter is 100 to 1000 times that of the Sun.

red dwarf A faint, cool, low-mass, main-sequence star.

white dwarf A dying star at the lower left of the H–R diagram that has collapsed to the size of Earth and is slowly cooling off.

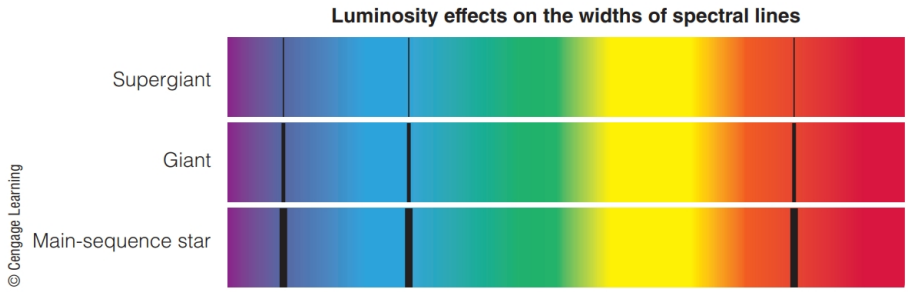


Figure 6.9 These schematic spectra show how the widths of spectral lines reveal a star's luminosity classification. Supergiants have very narrow spectral lines, and main-sequence stars have broad lines. Some spectral lines are more sensitive to this effect than others. Examining the details of a star's spectrum can determine its luminosity classification.

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Table 6.2 | Luminosity Classes

Class	Description	Example
Ia	Luminous supergiant	Rigel A
Ib	Regular supergiant	Polaris
II	Bright giant	Adhara
III	Giant	Capella
IV	Subgiant	Altair
V	Main sequence	Sun

The width of the spectral lines is clearly an indicator of how big a star is. As you learned earlier in this section, luminosity is dependent on both radius and temperature. So astronomers have further refined stellar classification by developing a **luminosity class** system that roughly designates the size of the star as well as its luminosity (see Table 6.2). Supergiants, for example, are very luminous because they are very large.

The luminosity classes are represented by the Roman numerals I through V, with supergiants further subdivided into types Ia and Ib. For example, you can distinguish between a luminous supergiant (Ia) such as Rigel (Beta Orionis) and a regular supergiant (Ib) such as Polaris, the North Star (Alpha Ursa Minoris). The star Adhara (Epsilon Canis Majoris) is a luminous giant (II), Capella (Alpha Aurigae) is a giant (III), and Altair (Alpha Aquilae) is a subgiant (IV). The Sun is a main-sequence star (V). The luminosity class notation appears after the spectral type, as in G2V for the Sun. Sometimes an additional class is utilized for white dwarfs (wd or D).

The approximate positions of the supergiant, giant, and main-sequence luminosity classes are shown on the H–R diagram. Luminosity class doesn't really define stellar luminosities, sizes, or temperatures very precisely. The H–R diagram in Figure 6.8 shows that supergiants (class I) have about the same luminosity but vary broadly in temperature and size. On the other hand, main-sequence stars (class V) have roughly the same size but vary greatly in both luminosity and temperature. Although luminosity classification is subtle and not very accurate, it is an important technique in modern astronomy because it provides clues to distance.

luminosity class A category of stars of similar luminosity, determined by the widths of lines in their spectra.

spectroscopic parallax The method of determining a star's distance by comparing its apparent magnitude with its absolute magnitude as estimated from its spectrum.

binary stars Pairs of stars that orbit around their common centre of mass.

Most stars are too distant to have measurable parallaxes, but astronomers can find the distances to these stars if they can record the stars' spectra and determine their luminosity classes. From spectral type and luminosity class, astronomers can estimate the star's absolute magnitude, compare with its apparent magnitude, and compute its distance. Although this process finds distance and not true parallax, it is called **spectroscopic parallax**.

For example, Betelgeuse (Alpha Orionis) is classified M2 Ia, and its apparent magnitude averages about 0.4 (Betelgeuse is somewhat variable). You can plot this star in an H–R diagram such as Figure 6.8, where you would find that a temperature class of M2 and luminosity class of Ib (supergiant) corresponds to a luminosity of about 30 000 $L_{\odot}$. That information, combined with the star's apparent brightness, allows astronomers to estimate that Betelgeuse is about 640 ly from Earth. (Refer to **Absolute Magnitude and Distance** in the Math Reference Cards.) The *Hipparcos* satellite finds the actual distance to be 427 ly, so the distance determined by the spectroscopic parallax technique is only approximate. Spectroscopic parallax does give a good first estimate of the distances of stars so far away that their parallax can't easily be measured.

6.5 Star Masses: Binary Stars

The fifth, and final, goal for this chapter is to find out how much matter stars contain; that is, to know their masses. Do they all contain about the same mass as the Sun, or are some more massive than others?

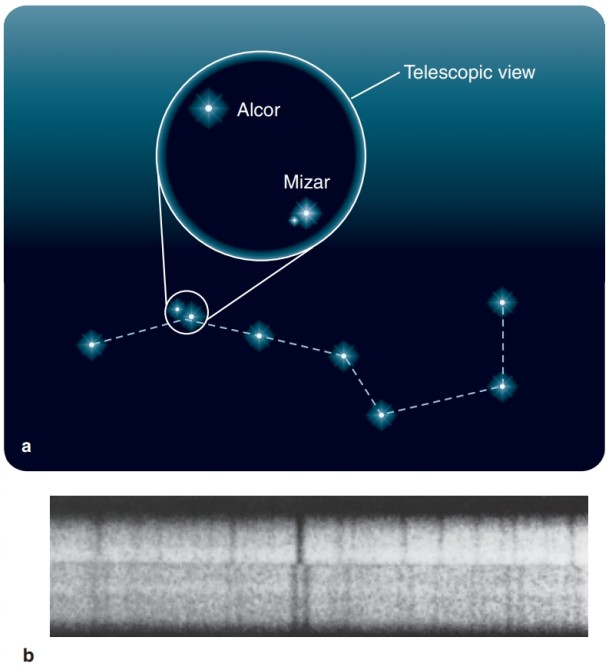
Gravity is the key to determining mass. Matter produces a gravitational field. Astronomers can figure out how much matter a star contains if they watch an object such as another star move through the star's gravitational field.

Finding the masses of stars involves studying **binary stars**, pairs of stars that orbit each other. This may come as a surprise, but many of the familiar stars in the sky are pairs of stars orbiting each other (see Figure 6.10). Binary systems are common; more than half of all stars are members of binary star systems. Few, however, can be analyzed completely. Many are so far apart that their periods are much too long for practical mapping of their orbits. Others are so close together they are not visible as separate stars.

Binary Stars in General

The key to finding the mass of a binary star is an understanding of orbital motion (see Chapter 3). Each star in a binary system moves in its own orbit around the system's

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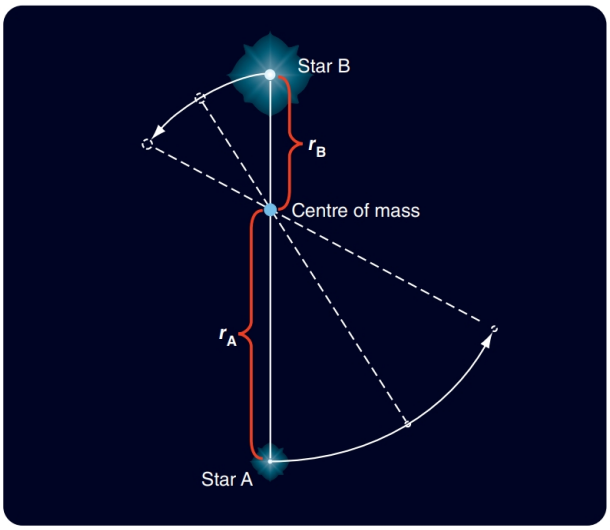


(a) © Cengage Learning (b) Courtesy the Observations of the Carnegie Institution of Washington

Figure 6.10 (a) At the bend of the handle of the Big Dipper lie a pair of stars, Mizar and Alcor. A telescope reveals that Mizar is a member of a visual binary system. (b) Spectra of these stars recorded at different times show that Mizar, its faint companion, and the nearby star Alcor are all spectroscopic binaries.

centre of mass: the balance point of the system (see **Visualizing Astronomy 3.2, Orbiting Earth**). If one star is more massive than its companion, the massive star is closer to the centre of mass and travels in a smaller orbit, while the lower-mass star whips around in a larger orbit (Figure 6.11). The ratio of the masses of the stars in the binary system portrayed in Figure 6.11 is M_A/M_B, which equals r_B/r_A, the inverse of the ratio of the radii of the orbits. For example, if one star in a binary system has an orbit twice as large as the other star's orbit, it must be half as massive. Getting the ratio of the masses is easy, but that doesn't tell you the individual masses of the stars, which is what you really want to know. That takes one more step.

To find the total mass of a binary star system, you must know the size of the orbits and the orbital period—the length of time the stars take to complete one orbit. The smaller the orbits are and the shorter the orbital period is, the stronger the stars' gravity must be to hold each other in orbit. From the sizes of the orbits and the orbital period, astronomers can use Kepler's third law (see Chapter 3) to figure out how much mass the stars contain in total. Combining that information with the ratio of the masses found from the relative sizes of the orbits reveals the individual masses of the stars. (Refer to **The Masses of Binary Stars** in the Math Reference Cards.)



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Figure 6.11 As stars in a binary star system revolve around each other, the line connecting them always passes through the centre of mass, and the more massive star is always closer to the centre of mass.

Finding the mass of a binary star system is easier said than done. One difficulty is that the true sizes of the star orbits must be measured in units such as metres or astronomical units to find the masses of the stars in units such as kilograms or solar masses. Measuring the true sizes of the orbits in turn requires knowing the distance to the binary system. Therefore, the only stars whose masses astronomers know for certain are the ones in binary systems with orbits that have been determined, and their distances from Earth have been measured. Other complications are that the orbits of the two stars may be elliptical, and that the plane of their orbits can be tipped at an angle to your line of sight, which distorts the apparent shapes of the orbits. Astronomers must find ways to correct for these complications. Notice that finding the masses of binary stars requires a number of steps to get from what can be observed to what astronomers really want to know: the masses. Constructing such sequences of steps is an important part of science. (See **How Do We Know? 6.1**.)

Three Kinds of Binary Systems

Although there are many different kinds of binary stars, three types are especially important for determining stellar masses. Studying binary stars is also preparation for knowing how to find planets around stars other than our Sun, because a star with a planet orbiting around it is like a binary star system with one very small component. Each type of binary star system corresponds to a different technique for finding planets, as you will learn in Chapter 12.

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HOW DO WE KNOW? 6.1



Chains of Inference

How do scientists measure something they can't detect? Sometimes scientists cannot directly observe the things they really want to study, so they must construct chains of inference that connect observable parameters to the unobservable quantities they want to know. You can't measure the mass of a star directly, so you must find a way to use what you can observe, orbital period and angular separation, to figure out step by step the parameters you need to calculate the mass.

Consider another example. Geologists can't measure the temperature and density of Earth's interior directly. There is no way to drill a hole to Earth's centre and lower a thermometer or recover a sample. However, the speed of vibrations from a distant earthquake depends on the temperature and density of the rock they pass through. Geologists can't measure the speed of the vibrations deep inside Earth; but they can measure the delays in the arrival times at different locations on the surface, and that allows them to work their way back to the speed and, finally, the temperature and density.

Chains of inference can be nonmathematical. Biologists studying the migration of whales can't follow individual whales for years at a time, but they can observe them feeding and mating in different locations; take into consideration food sources, ocean currents, and water temperatures; and construct a chain of inference that leads back to the seasonal migration pattern for the whales.

This chapter contains a number of chains of inference. Almost all fields of science use chains of inference. When you can link the observable parameters step by step to the final conclusions, you gain a strong insight into the nature of science.



USGS

San Andreas Fault: A chain of inference connects earthquakes to conditions inside Earth.

In a **visual binary system**, the two stars are separately visible in the telescope and astronomers can watch the stars orbit each other over periods of years or decades, as the series of illustrations of Sirius A and B in Figure 6.12 demonstrates. From that, astronomers can find the orbital period and, if the distance of the system from Earth can be found, the size of the orbits. That is enough to find the masses of the stars.

visual binary system A binary star system in which the two stars are separately visible in the telescope.

spectroscopic binary system A star system in which the stars are too close together to be visible separately. We see a single point of light, and only by taking a spectrum can we determine that there are two stars.

Many visual binaries have such large orbits their orbital periods are hundreds or thousands of years, and astronomers have not yet seen them complete an entire orbit. Also, many binary stars orbit so close to each other they are not visible as separate stars. Such systems can't be analyzed as a visual binary.

If the stars in a binary system are close together, a telescopic view, limited by diffraction and atmospheric seeing, shows a single point of light. Only by looking at a spectrum, which is formed by light from both stars and contains spectral lines from both, can astronomers tell that there are two stars present, not one. Such a system is a **spectroscopic binary system**. Familiar examples of spectroscopic binary systems are the stars Mizar and Alcor in the handle of the Big Dipper (Figure 6.10b).

Figure 6.13 shows a pair of stars orbiting each other; the circular orbit appears elliptical because you see it nearly edge-on. If this were a true spectroscopic binary system, you would not see the separate stars. Nevertheless, the Doppler shift would tell you there were two stars orbiting each other. As the two stars move in their orbits, they alternately approach toward and recede from Earth, and their spectral lines are Doppler shifted alternately toward blue and then red wavelengths. Noticing pairs of spectral lines moving

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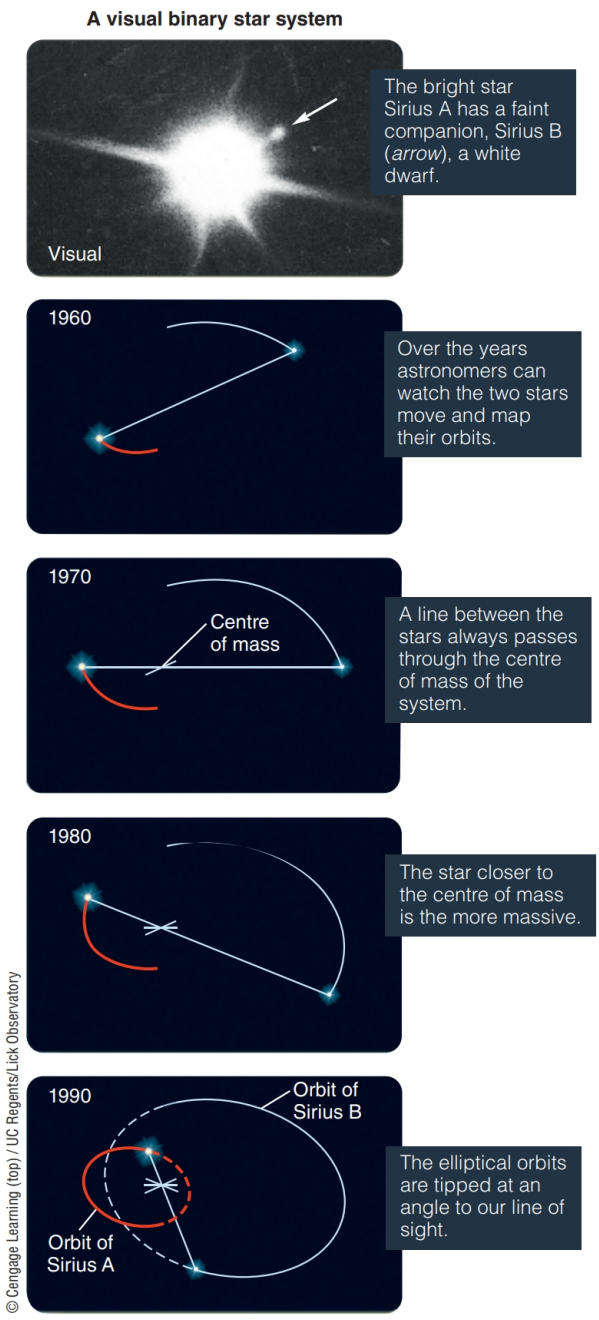


Figure 6.12 The orbital motion of Sirius A and Sirius B can reveal their individual masses.

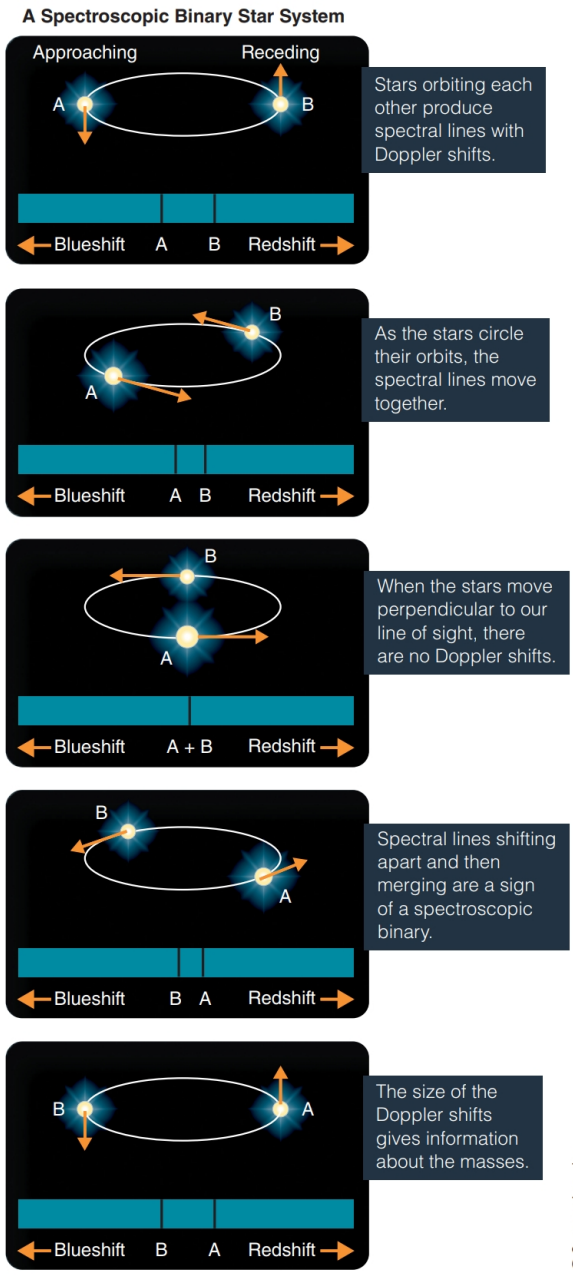


Figure 6.13 From Earth, a spectroscopic binary looks like a single point of light, but the Doppler shifts in its spectrum reveal the orbital motion of the two stars. If the plane of their orbits is oriented very close to edge-on, the stars can pass in front of each other as they orbit and the system will be an eclipsing binary, as illustrated in Figure 6.12.

back and forth across each other would alert you that you were observing a spectroscopic binary.

Although spectroscopic binaries are very common, they are not as useful as visual binaries. Astronomers can find the orbital period easily, but they can't find the true size of the orbits because there is no way to find the angle at which the orbits are tipped. That means they can't find the true masses of a spectroscopic binary. All they can find is a lower limit to the masses.

If the plane of the orbits is nearly edge-on to Earth, the stars can cross in front of each other as seen from Earth. When one star moves in front of the other, it blocks

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some of the light, and the star is eclipsed. Such a system is called an **eclipsing binary system**.

Seen from Earth, the two stars are not visible separately. The system looks like a single point of light. But, when one star moves in front of the other star, part of the light is blocked, and the total brightness of the point of light decreases. Figure 6.14 shows a smaller star moving in an orbit around a larger star, first eclipsing the larger star and then being eclipsed as it moves behind. The resulting variation in the brightness of the system is shown as a graph of brightness versus time, a **light curve**.

The light curves of eclipsing binary systems contain plenty of information about the stars, but the curves can be difficult to analyze. Figure 6.14 shows an idealized example of such a system. Once the light curve of an eclipsing binary system has been accurately observed, astronomers can construct a chain of inference that leads to the masses of the two stars. They can find the orbital period easily and can get spectra showing the Doppler shifts of the two stars. They can find the orbital speed because they don't have to correct for the inclination of the orbits; you know the orbits are nearly edge-on, or there would not be eclipses. From that, astronomers can find the size of the orbits and the masses of the stars.

Earlier in this chapter you learned that luminosity and temperature can be used to determine the radii of stars, but eclipsing binary systems give a way to check those calculations by measuring the sizes of a few stars directly. The light curve shows how long it takes for the stars to cross in front of each other, and multiplying these time intervals by the orbital speeds gives the diameters of the stars. There are complications due to the inclination and eccentricity of orbits, but often these effects can be taken into account, so observations of an eclipsing binary system can directly tell you not only the masses of its stars but also their diameters.

From the study of binary stars, astronomers have found that the masses of stars range from roughly 0.1 solar masses to nearly 100 solar masses. The most massive stars ever found in a binary system have masses of 83 and 82 solar masses. A few other stars are believed to be more massive, 100 solar masses to 150 solar masses, but they do not lie in binary systems, so astronomers can only estimate their masses.

eclipsing binary system A binary star system in which the stars cross in front of each other as seen from Earth.

light curve A graph of brightness versus time commonly used in analyzing variable stars and eclipsing binaries.

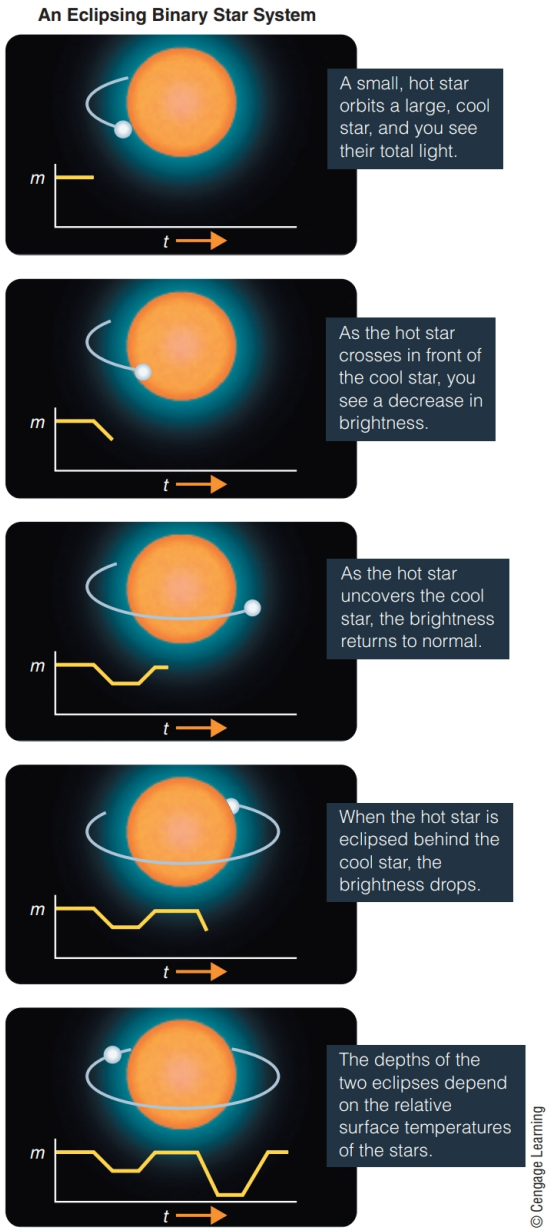


Figure 6.14 From Earth, an eclipsing binary looks like a single point of light, but changes in brightness reveal that two stars are eclipsing each other. The light curve, shown here as magnitude versus time, combined with Doppler shift information from spectra can reveal the size and mass of the individual stars.

6.6 Typical Stars

Having achieved the five goals for this chapter, you know how to find the distances, luminosities, temperatures, diameters, and masses of stars. Now you can put those data together to paint a family portrait of the stars. As in

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human family portraits, both similarities and differences are important clues to the history of the family.

Luminosity, Mass, and Density

The H–R diagram is filled with patterns that give you clues as to how stars are born, how they age, and how they die. When you add your data, you can see traces of those patterns.

If you label an H–R diagram with the masses of the stars determined by observations of binary star systems, you will discover the main-sequence stars are ordered by mass (see Figure 6.15). The most massive main-sequence stars are the hot stars. As you run your eye down the main sequence, you will find lower-mass stars, and the lowest-mass stars are the coolest, faintest, main-sequence stars.

Stars that do not lie on the main sequence are not in order according to mass. Some giants and supergiants are massive, while others are no more massive than the Sun. All white dwarfs have about the same mass, usually in the narrow range of 0.5 to about 1.0 solar masses.

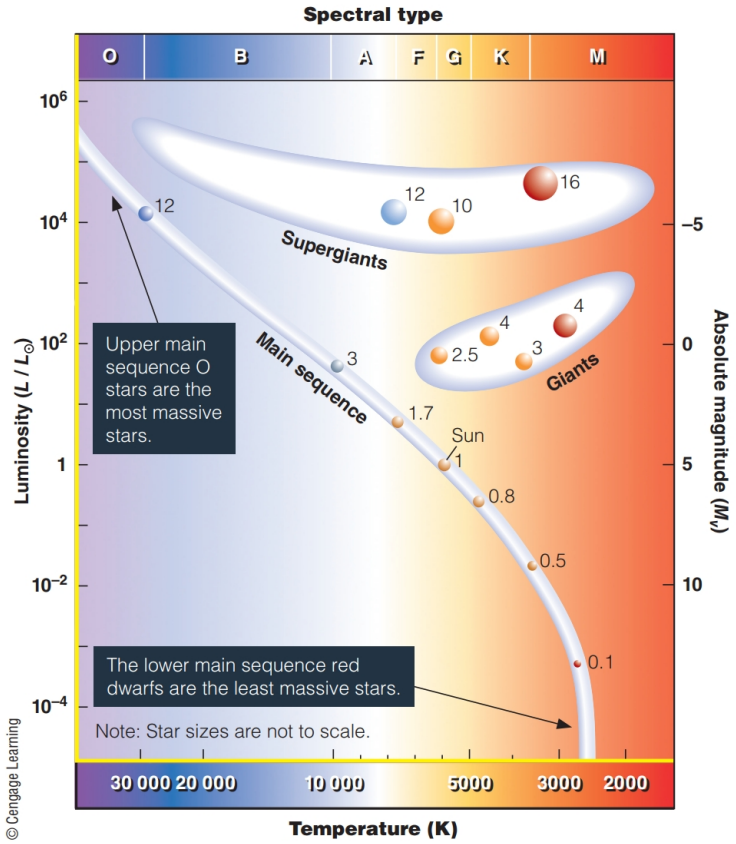


Figure 6.15 The masses of the plotted stars are labelled on this H–R diagram. Notice that the masses of main-sequence stars decrease from top to bottom, but the masses of giants and supergiants are not arranged in any ordered pattern.

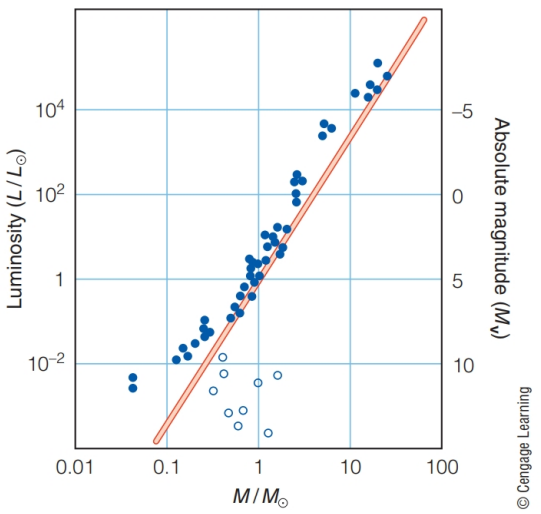


Figure 6.16 The mass–luminosity relation shows that the more massive a main-sequence star is, the more luminous it is. The open circles represent white dwarfs, which do not obey the relation.

Because of the systematic ordering of mass along the main sequence, these main-sequence stars obey a **mass–luminosity relation**: the more massive a star is, the more luminous it is (see Figure 6.16). In fact, the mass–luminosity relation can be expressed as follows: luminosity is proportional to mass to the 3.5 power. For example, a star with a mass of 4.0 $M_\odot$ can be expected to have a luminosity of about $4^{3.5}$ or 128 $L_\odot$. Giants, supergiants, and white dwarfs do not follow the mass–luminosity relation. In the next chapters, the mass–luminosity relation of main-sequence stars will help you understand how these stars generate their energy. (Refer to **The Mass–Luminosity Relation** in the Math Reference Cards.)

Though mass alone does not reveal any pattern among giants, supergiants, and white dwarfs, density does. Once you know a star's mass and diameter, you can calculate its average density by dividing its mass by its volume. Stars are not uniform in density; they are most dense in their cores and least dense near their surface. The centre of the Sun, for instance, is about 150 times as dense as water (or about 7.5 times as dense as gold); its density near the photosphere is about 3400 times less dense than Earth's atmosphere at sea level. A star's

mass–luminosity relation The more massive a main-sequence star is, the more luminous it is.

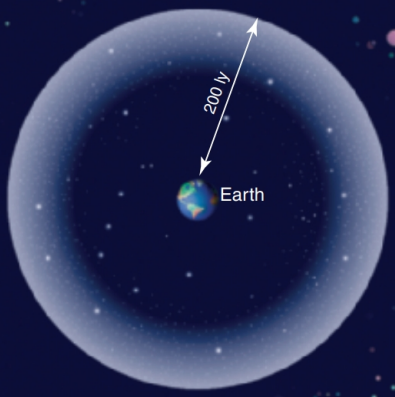
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Visualizing Astronomy 6.1

The Family of Stars

1 What is the most common type of star? What types of stars are rare? To answer these questions, you need to make a census of the stars. In doing so you collect information on their spectral classes, luminosity classes, and distances. Your survey of the family of stars produces some surprising demographic results.

1a You could survey the stars by observing every star within 200 ly of Earth. A sphere of 200 ly in radius encloses about 33.5 million cubic light years. Such a survey would tell you how many stars of each type are found within such a volume.



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2 Your survey faces two difficulties:

1. The most luminous stars are so rare you find only a few in your survey region. In fact, there is not even one O star within 200 ly of Earth.
2. Lower-main-sequence M stars—sometimes called red dwarfs—and white dwarfs are so faint they are hard to locate even when they are only a few light-years from Earth. Finding every one of these stars in your survey sphere is a difficult task, but if you don't, your survey is incomplete.

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The star chart in the background of these two pages shows most of the constellation Canis Major; stars are represented as dots with colours assigned according to spectral class. The brightest stars in the sky tend to be the rare, highly luminous stars, which appear bright even though they are far away. Most stars are of very low luminosity, so nearby stars tend to be very faint red dwarfs.

Spectral Class Color Key
- O and B
- A
- F
- G
- K
- M

Red dwarf
15 pc

ω^2 Canis Majoris
B3 Ia 790 pc

Red dwarf
17 pc

δ Canis Majoris
F8 Ia 550 pc

σ Canis Majoris
M0 Iab 370 pc

η Canis Majoris
B5 Ia 980 pc

ε Canis Majoris
B2 II 130 pc

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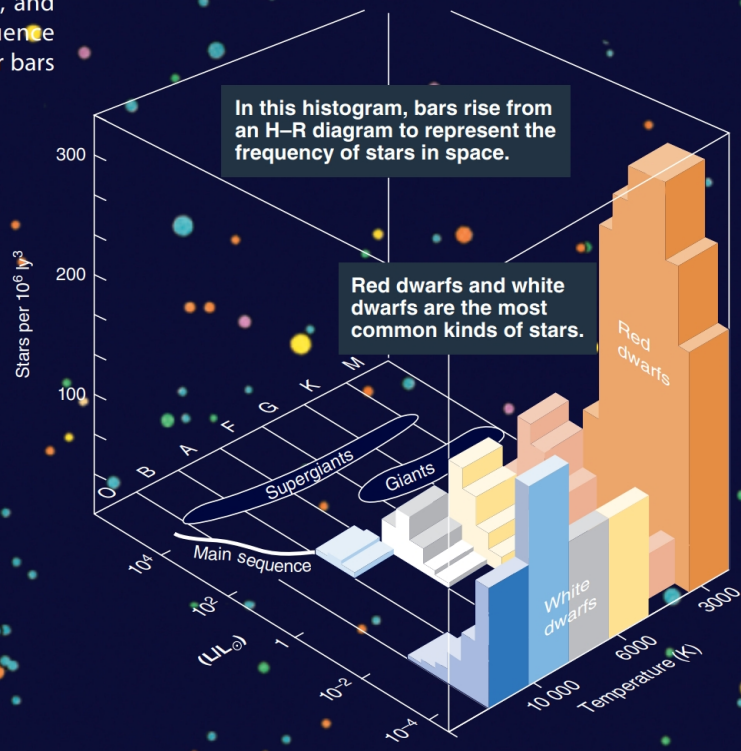
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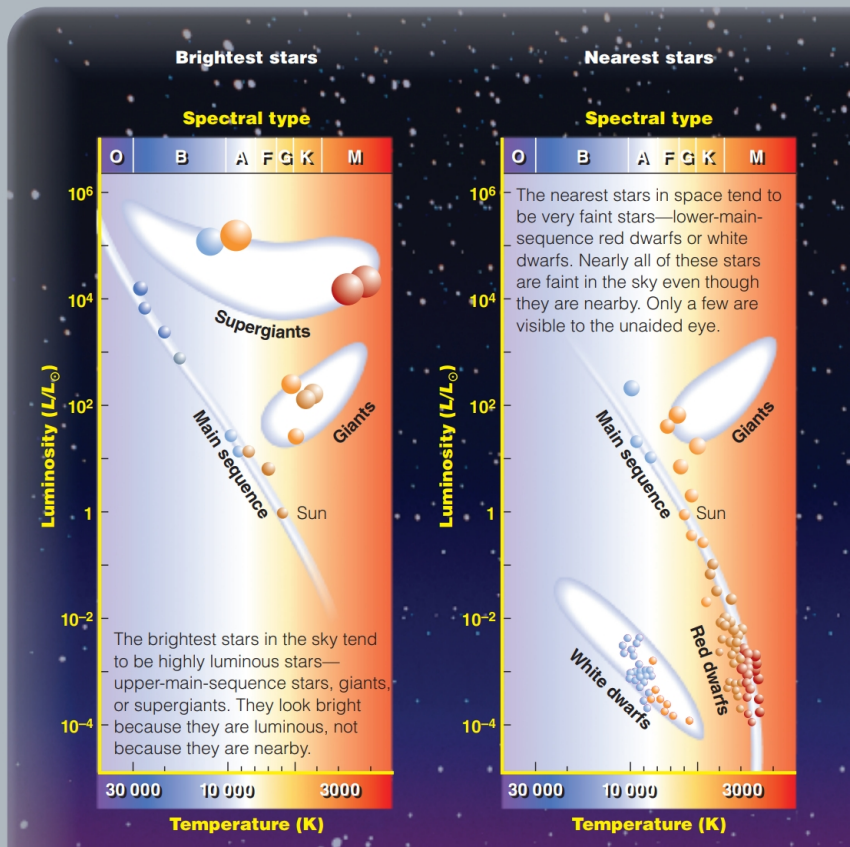
2a Supergiants, giants, and O and B main-sequence stars are so rare their bars are not visible in this graph.

Sirius A (α Canis Majoris) is the brightest star in the sky. With a spectral type of A1 V, it is not a very luminous star. It looks bright because it is only 2.6 pc away.

Sirius B is a white dwarf that orbits Sirius A. Although Sirius B is not very far away, it is much too faint to see with the unaided eye.



3 Luminous stars are rare but are also easy to see even at great distances. Most stars are very-low-luminous objects. Not a single white dwarf or red dwarf is bright enough to see with the unaided eye. See the H–R diagrams at right.



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CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Josef Pittner / Shutterstock.com

Algonquin Radio Observatory at Algonquin Park, Ontario

Arthur Edwin Covington

Arthur Covington, Canada's first radio astronomer, was a pioneer in microwave observations of our star—the Sun. He was the first to show that radio emissions from the Sun in the microwave region could be used as a measure of sunspot activity. This novel method of detecting sunspots is still used around the world today to study solar activity and its effects on radio communications.

Growing up in Saskatchewan and Vancouver, Covington showed an early interest in astronomy as well as in being an amateur radio operator. In 1942, he completed his doctoral degree in nuclear physics at University of California, Berkeley, and joined the National Research Council of Canada in Ottawa the same year, where he began developing new radar systems.

After World War II, Covington built a radio telescope out of surplus parts that operated in the microwave region around 10.7 cm. He noticed to his surprise that the Sun's microwave emissions did not simply follow the expected pattern of blackbody radiation, but instead were varying over time. He showed that this phenomenon was connected to sunspot activity, and his later studies contributed to the understanding of how sunspots are created.

Wanting to escape the interference of the growing "radio activity" of the Ottawa region in the late 1950s, Covington selected Algonquin Park (150 km northeast of Ottawa) as the site of a new radio telescope, the Algonquin Radio Observatory (ARO), becoming its director until his retirement in 1978. His research at the ARO provided evidence that major solar activity was preceded by microwave signals announcing, in effect, upcoming solar storms.

After Covington died in 2001, one of the buildings at the Herzberg Institute of Astrophysics in Penticton, BC, was named in his honour.

average density is intermediate between its central and surface densities. Interestingly, the Sun's average density is approximately 1 gram per cubic centimetre—about the density of water!

Main-sequence stars have average densities similar to the Sun's density. As you learned earlier in the discussion about luminosity classification, giant stars are much larger in diameter than the main-sequence stars but not much larger in mass, so giants have low average densities, ranging from 0.1 to 0.01 g/cm^3. The enormous supergiants have still lower densities, ranging from 0.001 to 0.000001 g/cm^3. These densities are thinner than the air you breathe, and if you could insulate yourself from the heat, you could fly an airplane through these stars. Only near the centre would you be in any danger; as you now know, astronomers calculate that the material there is very dense.

The white dwarfs have masses about equal to the Sun's mass, but in size are quite small: about the size of Earth. The matter is compressed to densities of 3 000 000 g/cm^3 or more. A teaspoonful of this material would have a mass of about 15 000 kg, or about the mass of two adult elephants.

Density divides stars into three groups. Most stars are main-sequence stars with densities similar to the Sun. Giants and supergiants are very low-density stars, and white dwarfs are high-density stars. You will see in later chapters that these densities reflect different stages in the evolution of stars.

Surveying the Stars

If you want to know what the average person thinks about a certain subject, you take a survey. If you want to know what the average star is like, you can survey the stars. Such surveys reveal important relationships among the family of stars. Over the years, many astronomers have added their results to the growing collection of data on star distances, luminosities, temperatures, sizes, and masses. They can now analyze those data to search for relationships between these and other parameters.

Modern astronomers are deeply involved in extensive surveys. Remember the earlier mention of the *Hipparcos* satellite that surveyed the entire sky, measuring the parallax of over a million stars? Powerful

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computers to control instruments and analyze data make such immense surveys possible. For example, the Sloan Digital Sky Survey mapped a quarter of the sky, measuring the position and brightness of 100 million stars and galaxies. Also, the Two Micron All Sky Survey (2MASS) has mapped the entire sky at three near-infrared wavelengths. A number of other sky surveys are underway. Astronomers will mine these mountains of data for decades to come.

What could you learn about stars from a survey of the stars near the Sun? The evidence astronomers have is that the Sun is in a typical place in the universe. Therefore, such a survey could reveal general characteristics of the stars. Study **Visualizing Astronomy 6.1, The Family of Stars**, and notice three important points:

1. Taking a survey is difficult because you must be sure to get a good sample. If you don't survey enough stars or if you miss some types of stars, your results could be biased.
2. A careful stellar survey reveals that what you see is deceptive. Most of the bright stars are not typical stars but instead are highly luminous giant and supergiant stars that can be seen from great distances.
3. Luminous stars are rare. Typical nearby stars have lower luminosity than our Sun. The most common stars are low-luminous red dwarfs.

The night sky is a beautiful carpet of stars. Some are giants and supergiants, and some are dwarfs. The family of stars is rich in its diversity. Pretend space is like a very clear ocean in which you are swimming. When you look at the night sky you are seeing mostly "whales," the rare very large and luminous stars, mostly far away. If instead you cast a net near your location, you would mostly catch "sardines," very-low-luminosity M dwarfs that make up most of the stellar population of the universe.

In this chapter you explored the basic properties of stars. Once you found the distance to the stars, you were able to find their luminosities. Knowing their luminosities and temperatures gives you their diameters. Studying binary stars gives you their masses. These are all rather mundane data. But you have now discovered a puzzling situation. The largest and most luminous stars are so rare you might joke that they hardly exist, and the average stars are such small low-mass things they are hard to see even if they are near Earth in space. Why does nature make stars in this peculiar way? To answer that question, you can explore the birth, life, and death of stars. That quest begins in the next chapter.

The **Big Picture**

We humans are medium creatures, and we experience medium things. You can see trees and flowers and small insects, but you cannot see the beauty of the microscopic world without ingenious instruments and special methods.

Similarly, you can sense the grandeur of a mountain range, but larger objects, such as stars, are too big for our medium senses. You have to use your ingenuity and imagination to experience the truth of such large objects. That is what science does for us. We live between the microscopic world and the astronomical world, and science enriches our lives by revealing the parts of the universe beyond our daily experience.

Experience is fun, but it is very limited. You may enjoy a flower by admiring its colour and shape and by smelling its fragrance. But the flower is more wonderful than your experience can reveal. To truly appreciate the flower you need to understand it: how complex it truly is, how it serves its plant, and how the plant came to create such a beautiful blossom.

Humans have a natural drive to understand as well as to experience. You have experienced the stars in the night sky, and now you are beginning to understand them as objects ranging from hot blue O stars to cool red M dwarfs. It is natural for you to wonder why these stars are so different. As you explore that story in the following chapters, you will discover that although you have medium senses, you can understand the stars.

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Review and Discussion Questions

Review Questions

1. Why are Earth-based parallax measurements limited to the nearest stars?
2. Why was the *Hipparcos* satellite able to make more accurate parallax measurements than ground-based telescopes?
3. What do the words *absolute* and *visual* mean in the definition of absolute visual magnitude?
4. What does luminosity measure that is different from what absolute visual magnitude measures?
5. Why are Balmer lines strong in the spectra of medium-temperature stars and weak in the spectra of hot and cool stars?
6. Why are titanium oxide features visible in the spectra of only the coolest stars?
7. Explain the interrelationships among Table 6.1, Figure 6.4, Figure 6.5, Figure 6.6, and Figure 6.8.
8. Why does the luminosity of a star depend on both its radius and its temperature?
9. How can you be sure that giant stars really are larger than main-sequence stars?
10. What evidence shows that white dwarfs must be very small?
11. What observations would you make to classify a star according to its luminosity? Why does that method work?
12. Why does the orbital period of a binary star depend on its mass?
13. What observations would you make to study an eclipsing binary star, and what would those measurements tell you about the component stars?
14. Why don't astronomers know the inclination of a spectroscopic binary? How do they know the inclination of an eclipsing binary?
15. How do the masses of stars along the main sequence illustrate the mass–luminosity relation?
16. Why is it difficult to find out how common the most luminous stars and the least luminous stars are?
17. What is the most common type of star?
18. If you look only at the brightest stars in the night sky, what type of star are you likely to be observing? Why?
19. **How Do We Know?** What is the missing link in the chain of inference leading from observations of spectroscopic binaries to the masses of stars?

Discussion Questions

1. If someone asked you to compile a list of the nearest stars to the Sun based on your own observations, how would you select your sample, what measurements would you make, and how would you analyze the measurements to detect nearby stars?
2. Can you think of classification systems used to simplify what would otherwise be complex measurements? Consider foods, movies, cars, grades, and clothes.
3. The Sun is sometimes described as an average star. Is that true? What is the average star really like?

STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *The Family of Stars*.

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
- Interactive Quizzing
- Animations
- Tutorials

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THE BRIGHT BLUE STAR at the centre of the Thor's Helmet Nebula is on the verge of a supernova explosion. Much of the nebula consists of hot gases expelled from the star. Winds from the star have also swept up interstellar gas and dust, creating a spectacular visual effect. The image was taken to celebrate the 50th anniversary of the European Southern Observatory (ESO). ESO is an intergovernmental organization with member nations from across Europe, all working together to operate a collection of world-class telescopes in Chile.

ESO/B. Bailleul

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PART TWO

7 The Structure and Formation of Stars



Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois Urbana-Champaign), and NASA

CHAPTER OUTLINE

7.1 Models of Stellar Structure
7.2 Nuclear Fusion in the Sun and Stars
7.3 Main-Sequence Stars
7.4 The Birth of Stars

GUIDEPOST

In the previous chapter you discovered the wide range of differences within the family of stars. In this chapter you will combine observations and hypotheses to understand how stars form, and learn the answers to five important questions:

- How do stars maintain their stability?
- How do stars generate energy?
- How do the luminosities and lifetimes of stars depend on their masses?
- How do astronomers study the gas and dust between the stars, called the interstellar medium?
- How do stars form from the interstellar medium?

The stars are not eternal. Almost every point of light in the night sky is an object like the Sun, held together by its gravity and generating tremendous energy in its core through nuclear reactions. The stars you see tonight are the same stars your parents, grandparents, and great-grandparents saw. Stars barely change over a human lifetime, but they are not eternal. Stars are born, and stars die. This chapter begins that story.

When trying to learn the secrets of the stars, we face some big challenges. How can we study the internal processes of stars when we can't see inside them? How can we map their life cycles when they live thousands or millions of times longer than any human? The answer lies in the methods of science. By constructing theories that describe how

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The giant nebula NGC 3603 shows the complete life cycle of stars. On the lower right, clouds of gas and dust are collapsing to form stars. In the centre, a cluster of young massive stars glow hot and blue. On the upper left, a blue supergiant star is nearing its ultimate supernova end.

Humans are natural-born scientists. When we're born, we want to know why the stars shine. We want to know why the sun rises.

Michio Kaku,
physicist and popular science communicator

Nature has always had a trick of surprising us, and she will continue to surprise us. But she has never let us down yet.

Cecilia Payne-Gaposchkin,
astronomer who first explained the chemical composition of stars

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nature works and then testing those theories against evidence from observations, you can unravel some of nature's greatest secrets. In this chapter, you will see how the flow of energy from inside to the surfaces of the stars balances gravity, making the stars stable, and how nuclear reactions inside stars generate that energy. You will also see how gravity creates new stars from the thin dusty gas between the stars.

7.1 Models of Stellar Structure

If there is a single idea in stellar astronomy that can be called crucial, it is the concept of balance. Every star is in a long-lasting yet ultimately temporary balance between the gravity produced by its own tremendous mass and the pressure generated by the nuclear reactions deep inside it.

Stars have internal structure. Like an onion or a peach, a star has different layers inside. Each layer is defined by its physical conditions, such as temperature and chemical composition. And just as an onion and a peach differ in their internal structures, different types of stars have different internal layers. We can't see the interiors of stars, so how can we know what their structures are like? We do this by building a **stellar model**.

Models are very important in science. They let us understand phenomena that are well beyond our personal experience and often beyond our ability to directly observe. Models combine observations or measurements of the natural world, plus the physical laws required to interpret those observations, to produce a table of numbers describing the desired attributes of a physical system. We can make a simple model of a star by imagining it to be a sphere divided into many thin, concentric layers, like an onion. Using a computer, we keep track of the properties of the material in each layer, such as its mass, temperature, density, pressure, and chemical composition.

stellar model A table of numbers and associated equations describing the conditions in various layers within a star.

conservation of mass A basic physical law saying that matter cannot be created out of nothing and cannot vanish into nothing. Only its form can change.

conservation of energy One of the basic laws of stellar structure: The total luminosity must equal the sum of energy generated in all of the layers.

Table 7.1 Four Laws of Stellar Structure

I. Conservation of mass	The mass of a star equals the sum of the masses of its layers.
II. Conservation of energy	The luminosity of a star equals the sum of the energy generated in all the layers.
III. Energy transport	Energy moves from hot to cool regions by conduction, radiation, or convection.
IV. Hydrostatic equilibrium	The weight compressing each layer is balanced by the pressure in that layer.

Then we use the laws of physics to compute how the properties of each layer depend on the ones around it. For example, if the layers near the centre are very hot, but those above them are cooler, then energy will tend to diffuse outward from the hot core to the cool outer layers. This is the principle of energy transport—one of the four physical laws we require to understand the structures of stars (Table 7.1).

In the following sections, we'll discuss these four laws and use them to investigate not only the insides of stars, but also how stars are born in the first place.

The Laws of Conservation of Mass and Energy

Two of the most important laws governing stellar structure are what astronomers and physicists call *conservation* laws. Conservation laws say that certain things cannot be created out of nothing or vanish into nothing. Such conservation laws are powerful aids to help you understand how nature works.

In the context of a star, the law of **conservation of mass** says that the total mass of the star must equal the sum of the masses of all of the layers. Mass cannot be created or destroyed, although it can be converted to energy. As we shall shortly see, this conversion of mass to energy is the ultimate power source of stars.

The law of **conservation of energy** is another basic law of nature. It says that the amount of energy flowing out of the top of a layer in the star must be equal to the amount of energy coming in at the bottom, plus whatever energy is generated within the layer. That means the energy leaving the surface of the star—its *luminosity*—must equal the sum of the energies generated in all the layers inside the star through fusion. This is like saying

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that the total number of new cars driving out of a factory must equal the sum of all the cars made on each of the production lines.

Energy Transport

The conservation of energy means that energy cannot be created or destroyed, it can only move around or be converted from one form to another. We know intuitively that energy has a tendency to move away from where it was generated. The heat from a candle rises away from the flame, or the light from a light bulb spreads throughout a room. The law of **energy transport** says that energy must flow from hot regions to cooler regions by one of three methods: conduction, radiation, or convection.

Conduction is the most familiar form of heat flow. If you hold the bowl of a spoon in a candle flame, the handle of the spoon grows warmer as heat, in the form of motion among the atoms of the spoon, is conducted from atom to atom up the handle (Figure 7.1). Conduction requires close contact between the atoms. It is not an important means of energy transport in normal stars because their atoms tend to be separated widely enough that radiation or convection are much more efficient, even in their centres. Conduction is important only in rare types of stars with extremely high densities.

The transport of energy by *radiation* is another familiar experience. Put your hand near a candle flame, and you can feel the heat. What you actually feel are infrared photons—packets of energy—radiated by the flame and absorbed by your hand. Radiation is the principal means of energy transport in the interiors of most stars. Photons are absorbed and re-emitted in random directions over and over as energy works its way from the hot interior toward the cooler surface.

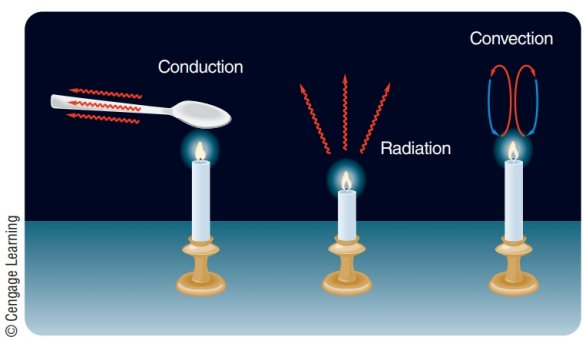


Figure 7.1 The three modes by which energy may be transported from the flame of a candle, as shown in this figure, are the three modes of energy transport within a star. Radiation and convection are much more important than conduction in the interiors of main-sequence stars.

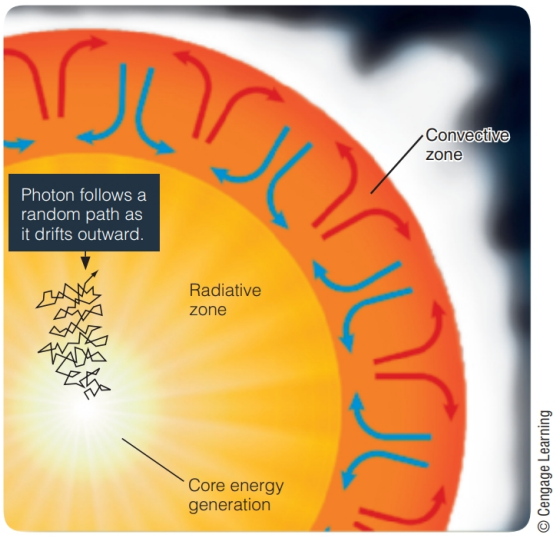


Figure 7.2 A cross-section of the Sun. Near the centre, nuclear fusion reactions sustain high temperatures. Energy flows through the radiative zone as photons are randomly deflected over and over by electrons. In the cooler, more opaque outer layers the energy is carried by rising convection currents of hot gas (red arrows) and sinking currents of cooler gas (blue arrows).

The flow of energy by radiation depends on how difficult it is for photons to move through the gas. If the gas has a high **opacity**, radiation will not flow freely. When radiation can't flow freely, the energy backs up like water behind a dam. When enough heat builds up, the gas begins to churn as hot gas rises upward and cool gas sinks downward. This heat-driven circulation of a fluid is called *convection*, the third mechanism of energy transport in stars. You are familiar with convection; the rising wisp of smoke above a candle flame is carried by convection. The cross-section of the Sun shown in Figure 7.2 indicates the location of the radiative and convective zones.

How can we apply this law to build a model of a star? Stars generate colossal amounts of energy in their cores, and this energy must flow through their layers and escape their surfaces, producing the visible light and other forms of radiation that constitute a star's luminosity. For each layer, we can say that the amount of energy entering a layer of our model should equal the amount of energy leaving it, if the layer is to remain balanced. But the *way* energy flows through the layer will depend on conditions such as its temperature and density. This turns out to be critically important, because energy flows in very different ways in different stars.

energy transport The principle that energy must move from hot to cool regions by conduction, radiation, or convection.

opacity The resistance of a gas to the passage of radiation.

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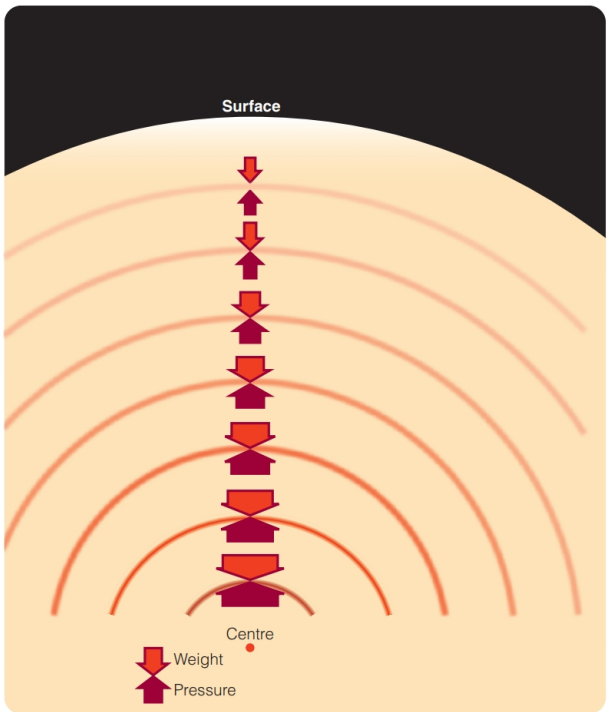
Hydrostatic Equilibrium

A star is a battle between pressure and gravity. The immense heat generated at the core of a star drives the star to expand, while the gravity generated by the star's tremendous mass threatens to crush it. For a star to remain stable, neither expanding nor contracting, the weight of each of its layers must be supported by the layers below. (The words *down* or *below* are conventionally used to refer to regions closer to the centre of a star, because that's the direction gravity pulls.) Picture a pyramid of people in a circus stunt—the people in the top row do not have to hold up anybody else; the people in the next row down are holding up the people in the top row; and so on. In a stable star, the deeper layers must support the weight of all of the layers above. The inside of a star is made up of gas, so the weight pressing down on a layer must be balanced by gas pressure in that layer. If the pressure is too low the weight from above will compress and push down the layer; if the pressure is too high the layer will expand and lift the layers above.

This balance between weight and pressure is called **hydrostatic equilibrium**. *Hydro*, from the Greek word for water, tells you the material is a fluid (fluids can be either liquids or gases; in stars, it is the gaseous definition that applies). *Static* tells you the fluid is stable, neither expanding nor contracting.

Figure 7.3 shows this hydrostatic balance in the imaginary layers of a star. The star's own gravity pulls inward on each layer. The weight pressing down on each layer is shown by light-red arrows, which grow larger with increasing depth because the weight grows larger. The pressure in each layer is shown by dark-red arrows, which must grow larger with increasing depth to support the weight above.

The pressure in a gas depends on the temperature and density of the gas. Near the surface, there is little weight pressing down, so the pressure does not need to be high for stability. Deeper in the star, the pressure must be higher than at the surface, which means that the temperature and density of the gas must also be higher. Hydrostatic equilibrium tells you that stars must have high temperature, pressure, and density inside to support their own weight and be stable.



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Figure 7.3 The principle of hydrostatic equilibrium says the pressure in each layer of a star must balance the weight on that layer. Consequently, as the weight increases from the surface of the star to its centre, the pressure must also increase.

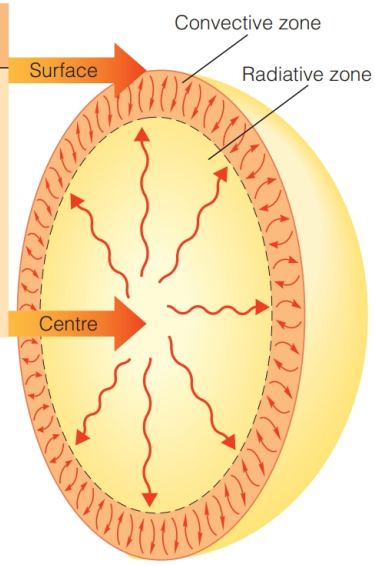
A Complete Stellar Model

The laws of stellar structure, described in general terms in the previous sections, allow us to build a complete model of a star. To begin constructing a model, we can fix the temperature, luminosity, diameter, and chemical composition of the outermost layer in the model to be the values we observe for a real star, as discussed in Chapter 6. We can set the sum of the masses of all the layers equal to the measured mass of the star, and so on with its other measurable properties. Then, we apply the mathematical forms of the laws of stellar structure to each of the layers in the model, solving the equations to arrive at a complete picture of conditions throughout the interior of the star. We can read the model as a table of numbers, or render it visually. The table shown in Figure 7.4 is a model of the Sun. The bottom line, for radius equal to 0.00, represents the centre of the Sun, and the top line, for radius equal to 1.00, represents the surface. The other lines tell you the temperature and density in each shell, the mass inside each shell, and the fraction of the Sun's luminosity flowing outward through the shell. The bottom line tells you that the temperature at the centre of the Sun must be over 15 million Kelvin in order for the Sun to be stable. At such a high temperature, the gas is very transparent, and energy flows as radiation. Nearer the surface, the temperature is lower, the gas is more opaque, and energy moves by convection. This is confirmed by evidence of convection visible on the Sun's surface (see Chapter 5).

hydrostatic equilibrium One of the basic laws of stellar structure: The weight on each layer must be balanced by the pressure in that layer.

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$R / R_\odot$	T (10^6 K)	Density (g/cm^3)	$M / M_\odot$	$L / L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.2	0.035	0.996	1.00
0.70	2.3	0.12	0.990	1.00
0.60	3.1	0.40	0.97	1.00
0.50	4.9	1.3	0.92	1.00
0.40	5.1	4.1	0.82	1.00
0.30	6.9	13.	0.63	0.99
0.20	9.3	36.	0.34	0.91
0.10	13.1	89.	0.073	0.40
0.00	15.7	150.	0.000	0.00



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Figure 7.4 A stellar model is a table of numbers that represent conditions inside a star. Such tables can be computed using the four governing principles of stellar structure. The table in this figure describes the present-day Sun.

Stellar models also let you look into a star's past and future. In fact, you could use models as time machines to follow the evolution of stars over billions of years. To look into a star's future, for instance, you could use a stellar model to determine how fast the star uses its fuel in each shell. As the fuel is consumed, the chemical composition of the gas changes, the opacity changes, and the amount of energy generated declines. By calculating the rate of these changes, you could predict what the star will look like at some time in the future. You could repeat that process over and over and follow the evolution of the star step-by-step as it ages. The summaries of star formation and stellar evolution in this chapter and the next are based on thousands of stellar models constructed in this way.



HOW DO WE KNOW? 7.1

Mathematical Models

How can scientists study aspects of nature that cannot be observed directly? One of the most powerful tools in science is the mathematical model, a group of equations or a computer program carefully designed to describe the behaviour of the object that scientists want to study.

Many sciences use mathematical models. Medical scientists have created mathematical models of the nerves that control the heart, and physicists have made mathematical models of the inside of an atomic nucleus. Earth scientists have mathematical models of Earth's atmosphere and interior. In each case, the mathematical model allows scientists to study something that is difficult or unsafe to manipulate directly. A model can reveal regions scientists cannot observe, speed up a slow process, slow down a fast process, or allow scientists to perform experiments that would be impossible in reality. Astronomers, for example, can change the abundance of different chemical elements in a model star to see how its structure depends on its composition. Mathematical modelling is one of the most important research methods in astronomy.

As is true for any scientific model, a mathematical model is only as reliable as the data and assumptions that go into its creation. The celestial sphere (Chapter 2) is an adequate model of the sky for understanding the daily march of the stars across the sky, but it fails to explain the detailed motions of the planets. The same is true of mathematical models: their applicability is limited by the accuracy of their assumptions and the data used to generate them. They must be continually compared with observations of the real world, then revised accordingly to produce an even deeper understanding.

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7.2 Nuclear Fusion in the Sun and Stars

For thousands of years, the Sun's power source was a mystery. Simple calculations show that chemical reactions, such as the oxidation reaction we call fire, could power the Sun for thousands of years. Yet the geologic record on Earth clearly shows that our planet has been warmed by the Sun for *billions* of years. What could have powered the Sun for so long? The answer lies in the forces that hold atomic nuclei together.

Nuclear Binding Energy

The Sun generates its energy by breaking and reconnecting the bonds between the particles inside atomic nuclei. That is quite different from the way we generate energy by burning wood in a fireplace. The process of burning wood extracts energy by breaking and reconnecting chemical bonds between atoms in the wood. Chemical bonds are formed by interactions among the electrons in atoms. You saw in Chapter 5 that the electrons are bound to the atoms by electromagnetic force. Thus, chemical energy originates in the electromagnetic force.

There are only four known forces in nature: the force of gravity, the electromagnetic force, and the strong and weak **nuclear forces**. The weak nuclear force is involved in the radioactive decay of certain kinds of nuclear particles, and the strong force binds together atomic nuclei. Nuclear energy originates in the strong nuclear force.

Nuclear power plants on Earth generate energy through **nuclear fission** reactions that split uranium nuclei into less massive fragments. In a uranium nucleus, the protons and neutrons are bound tightly together by the strong nuclear force. However, when the nucleus splits apart in a fission reaction, the protons and neutrons in the resulting smaller nuclei are even more tightly bound than those in the original uranium nucleus. This is shown in Figure 7.5: splitting a massive atom, such as uranium, results in products that are more tightly bound. The excess binding energy is released in the reaction.

nuclear forces The two forces of nature that govern interactions among particles in the nuclei of atoms.

nuclear fission Reactions that break the nuclei of atoms into fragments.

nuclear fusion Reactions that join the nuclei of atoms to form more massive nuclei.

You can think of changes in "binding energy" in analogy with water moving through a hydroelectric dam. The water at the top of a dam is farther away from the centre of gravity of Earth than the water at the bottom of the dam, so it is less "tightly bound" by gravity. As the water falls from the top of the dam to the bottom, it releases gravitational potential energy and joins the water at the bottom in the tightly bound state. The release of potential energy by the falling water causes the turbine to turn. When we take a less tightly bound state and convert it into a more tightly bound one, energy is released.

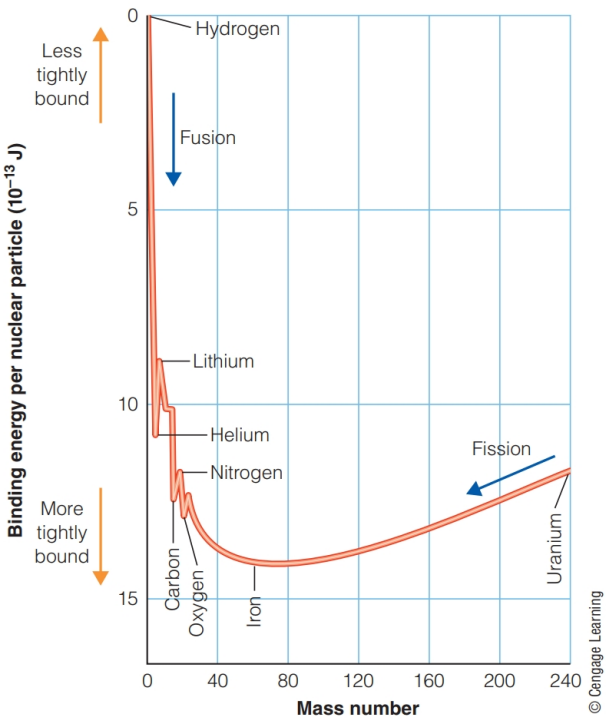


Figure 7.5 The red line in this graph shows the binding energy (the energy that holds an atomic nucleus together) for different types of atoms, which depends on atomic mass (the number of protons and neutrons in an atom's nucleus). Fission and fusion reactions that convert fuel nuclei to more tightly bound product nuclei will release energy. Iron has one of the most tightly bound nuclei, so nuclear reactions beginning with iron tend to consume energy.

Stars generate energy through **nuclear fusion** reactions that combine light nuclei into heavier nuclei. The most common reaction in stars fuses hydrogen nuclei (single protons) into helium nuclei (two protons and two neutrons). Hydrogen atoms are less tightly bound than helium atoms, so fusing hydrogen to produce helium releases energy. This is ultimately what powers stars.

Notice in Figure 7.5 that fusion of light particles and fission of heavy ones both tend to produce nuclei that are more tightly bound that the ones we started with. So, both of these processes release energy. However, there's a limit to both processes: iron has one of the most tightly bound of

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all atomic nuclei, so fusion or fission reactions beginning with iron tend to *consume* energy rather than produce it. We will see in Chapter 8 that this property of iron has important implications for the deaths of massive stars.

Fusion is a nuclear reaction, unrelated to the chemical reaction called fire. Even so, astronomers still sometimes get lazy and say things like "Stars burn hydrogen." Remember that this language is a shorthand that can give a false impression about how stars work.

Hydrogen Fusion

We said earlier that energy and mass are both "conserved," meaning that their total amounts in a closed system should not change. With his famous equation, $E = mc^2$, Albert Einstein showed us that, while neither mass nor energy can be destroyed, they can be converted into one another. It is actually the total "mass-energy" of a closed system that is conserved, so that if some mass is lost in a reaction it must emerge as energy. This is what happens during the nuclear fusion reactions that power stars.

In its core, the Sun fuses four hydrogen nuclei to make one helium nucleus. Because one helium nucleus contains 0.7 percent less mass than four hydrogen nuclei, some mass vanishes in the process. That mass is converted to an amount of energy given by $E = mc^2$. For example, converting 1 kg of matter completely into energy would produce an enormous amount of energy, 9×10^{16} joules, comparable to the amount of energy a big city such as Calgary uses in a year. (Refer to **Hydrogen Fusion** in the Math Reference Cards.)

Making one helium nucleus by fusing hydrogen nuclei releases a tiny amount of energy. Producing the Sun's immense luminosity requires 10^{38} of these reactions per second, transforming 5 million tonnes of mass into energy every second. That might sound as if the Sun is losing mass at a furious rate, but in its entire 10-billion-year lifetime, the Sun will convert less than 0.07 percent of its mass into energy.

Fusion reactions can occur only when the nuclei of two atoms get very close to each other. Because atomic nuclei carry positive charges, they repel each other with an electrostatic force called the Coulomb force. Physicists commonly refer to this repulsion between nuclei as the **Coulomb barrier**. To overcome this barrier, atomic nuclei must undergo violent collisions. These conditions rarely occur unless the gas is very hot, meaning that the particles of the gas are moving very quickly, on average. (Recall that an object's temperature is just a measure of the average speed with which its particles move.) Although the core temperature of the Sun is not high enough to allow most protons to overcome the Coulomb barrier, a quantum mechanical effect allows some protons to "tunnel through" the Coulomb barrier and fuse with one another.

Nuclear reactions in the Sun take place only near the centre, where the gas is hot and dense. A high temperature ensures that collisions between nuclei are energetic enough to tunnel through the Coulomb barrier, and a high density ensures that there are enough collisions, and thus enough reactions, to produce enough energy to keep the Sun stable.

You can symbolize this process with a simple nuclear reaction:

$$4\ {}^{1}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \text{energy}$$

In this equation, ^{1}H represents a proton, the nucleus of a hydrogen atom, and ^{4}He represents the nucleus of a helium atom. The superscripts indicate the total numbers of protons and neutrons in each nucleus.

The actual steps in the process are more complicated than this simple summary suggests. Instead of waiting for four hydrogen nuclei to collide simultaneously, which would be a highly unlikely event, the process can proceed by steps in a series of reactions called the proton–proton chain.

The **proton–proton chain** is a series of three nuclear reactions that builds a helium nucleus by adding protons one at a time. This process is efficient at temperatures above 10 000 000 K. The Sun, for example, generates its energy in this way. Recall from the previous section that models of the interior of the Sun based on its overall stability indicate the central temperature is about 15 000 000 K.

The three reactions in the proton–proton chain are:

$$\begin{aligned} {}^{1}\mathrm{H} + {}^{1}\mathrm{H} &\rightarrow {}^{2}\mathrm{H} + e^{+} + \nu \\ {}^{2}\mathrm{H} + {}^{1}\mathrm{H} &\rightarrow {}^{3}\mathrm{He} + \gamma \\ {}^{3}\mathrm{He} + {}^{3}\mathrm{He} &\rightarrow {}^{4}\mathrm{He} + {}^{1}\mathrm{H} + {}^{1}\mathrm{H} \end{aligned}$$

In the first reaction, two hydrogen nuclei (two protons) combine, and one changes into a neutron, resulting in a heavy hydrogen nucleus called **deuterium**, while emitting a particle called a **positron** (a positively charged electron, symbolized by e^{+}) and another called a **neutrino** (ν). A

Coulomb barrier The electrostatic force of repulsion between bodies of like charge, commonly applied to atomic particles.

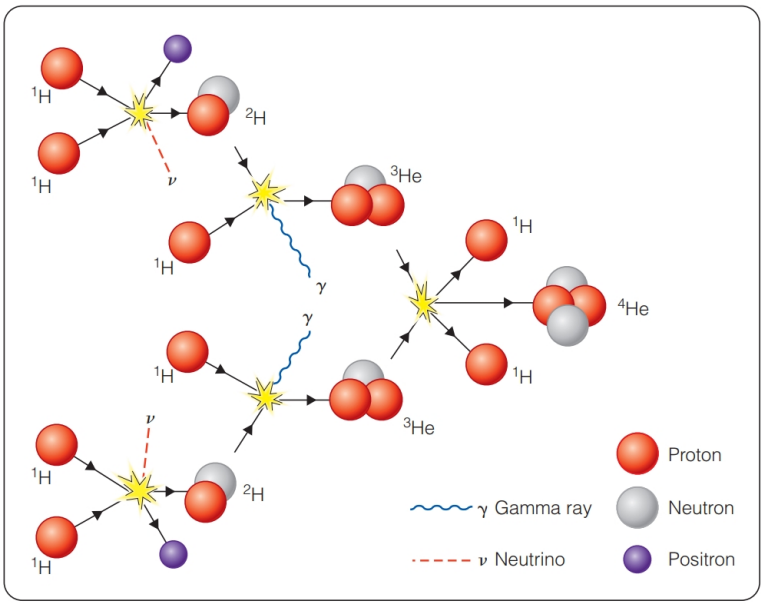
proton–proton chain A series of three nuclear reactions that build a helium atom by adding together protons; the main energy source in the Sun.

deuterium An isotope of hydrogen in which the nucleus contains a proton and a neutron.

positron The antimatter equivalent of the electron; it has all the same properties as the electron except that its charge is positive instead of negative.

neutrino A neutral, nearly massless atomic particle that travels near the speed of light.

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Figure 7.6 The proton–proton chain combines four protons (at far left) to produce one helium nucleus (at right). Energy is produced mostly as gamma rays and as positrons, which combine with electrons and convert their mass into more energy in the form of gamma rays. Neutrinos escape without helping to heat the gas.

positron is the antimatter counterpart of an electron. When an electron and a positron collide they annihilate each other and their mass gets converted completely into energy in the form of gamma rays—which is what happens to the positrons produced in the first reaction. In the second reaction, the heavy hydrogen nucleus absorbs another proton and, with the emission of a gamma ray (γ), becomes a lightweight helium nucleus (^{3}He). Finally, two light helium nuclei combine to form a normal helium nucleus (^{4}He) and two hydrogen nuclei. Because the last reaction needs two ^{3}He nuclei, the first and second reactions must occur twice for each ^{4}He produced (see Figure 7.6). The net result of this chain reaction is the transformation of four hydrogen nuclei into one helium nucleus plus energy.

All main-sequence stars fuse hydrogen into helium to generate energy. The Sun and smaller stars fuse hydrogen by the proton–proton chain. Upper-main-sequence stars, more massive than the Sun, fuse hydrogen by a more efficient process called the **CNO (carbon–nitrogen–oxygen) cycle**. The CNO cycle begins with a carbon nucleus and transforms it first into a nitrogen nucleus, then into an oxygen nucleus, and then back to a carbon nucleus. The carbon is unchanged in the end, but along the way four hydrogen nuclei are fused to make a helium nucleus plus energy, just as in the proton–proton chain. A carbon nucleus has six times more positive electric charge than hydrogen, so the Coulomb barrier is higher than for combining two protons. Temperatures higher than 16 000 000 K are required to make the CNO cycle work: the centre of the Sun is not quite hot enough for this reaction. In stars more massive than about 1.1 solar masses, the cores are hot enough and the CNO cycle dominates over the slower proton–proton chain.

CNO (carbon–nitrogen–oxygen) cycle A series of nuclear reactions that use carbon as a catalyst to combine four hydrogen nuclei to make one helium nucleus plus energy; effective in stars more massive than the Sun.

In both the proton–proton chain and the CNO cycle, the products include gamma rays, positrons, and neutrinos. The gamma rays are photons that are absorbed by the surrounding gas before they can travel more than a few centimetres. This heats the gas. The positrons produced in the first reaction combine with free electrons and both particles vanish, converting their mass into more gamma rays. In this way, the positrons also help keep the centre of the star hot. The neutrinos, however, are particles that travel at nearly the speed of light and almost never interact with other particles. The average neutrino could pass unhindered through a lead wall more than one light-year thick. Consequently, the neutrinos do not help heat the gas but race out of the star, carrying away roughly 2 percent of the energy produced.

It is time to ask the critical question that lies at the heart of science: What is the evidence to support this theoretical explanation of how the Sun and other stars generate energy? The search for that evidence introduces you to one of the great triumphs of modern astronomy.

Neutrinos from the Sun's Core

Nuclear reactions in the Sun's core produce floods of neutrinos that rush out of the Sun and off into space. If you could detect these neutrinos you could probe the Sun's interior.

Because neutrinos almost never interact with atoms, neutrinos are extremely hard to detect. You never feel the flood of over 10^{12} solar neutrinos that flows through your body every second. Even at night, neutrinos from the Sun rush through Earth as if it weren't there, up through your bed, through you, and onward into space. Certain particle reactions, however, can be triggered by a neutrino of the right energy.

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Beginning in the 1960s, astrophysicists found several ways to detect solar neutrinos. Initial measurements, however, detected too few neutrinos—about one-third as many as predicted by models of the Sun's interior. This discrepancy is known as the *solar neutrino problem*.

The Sudbury Neutrino Observatory (SNO) was constructed in an active nickel mine in Sudbury, Ontario, by a Canadian-led international group of scientists (Figure 7.7). The neutrino detector was located in a rock cavern located two kilometres underground. It consisted of a clear plastic sphere, 12 m in diameter, filled with 1000 tonnes of heavy water (water in which the hydrogen has been replaced by its heavier isotope, deuterium), and surrounded by a shell of 9600 ultrasensitive phototubes immersed in ultrapure ordinary water. Neutrinos were detected by three types of reactions in the heavy water, each producing distinctive tiny flashes of light. The detector was deep enough underground to filter out almost all cosmic rays that would produce false signals. The heavy water also enabled the detection of all three kinds of neutrinos, which physicists call "flavours."

The collection of data began in 1999 and, by June 2001, the detector had conclusively solved the solar neutrino problem. It showed that the "missing" two-thirds of

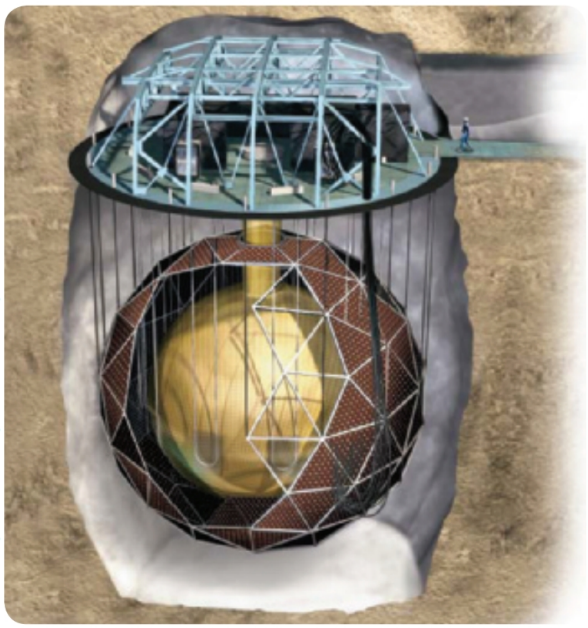


Photo courtesy of SNO - Sudbury Neutrino Observatory

Figure 7.7 The Sudbury Neutrino Observatory was a globe 12 m in diameter containing water rich in deuterium in place of ordinary hydrogen. Buried 2100 m deep in an Ontario mine, it could detect all three flavours of neutrinos, and confirmed that neutrinos can change their flavour as they travel.

CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY

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Art McDonald

Art McDonald

Most astronomers want to build their telescopes on the tops of tall mountains or in space. Not Art McDonald. His "telescope" was built more than 2 km underground, in an active nickel mine in Sudbury, Ontario. The Sudbury Neutrino Observatory (SNO) was designed to detect neutrinos—elusive particles emitted in copious quantities by nuclear reactions in the core of the Sun. The Standard Model of particle physics predicted that neutrinos should come in three "flavours" and that they should be massless. However, early neutrino detectors had failed to identify the expected number of neutrinos coming from the Sun. Art McDonald and his research collaborators created SNO to solve this problem. Building their detector deep underground helped shield it from cosmic rays and other energetic particles that would have overwhelmed it on the surface of Earth. They began their observations in 1999, and within a few years they had solved the "solar neutrino problem." Not only did neutrinos have mass, but they could oscillate from one flavour to another. Previous detectors had mainly been sensitive to one of the three flavours of neutrinos, which explained why they had found only about a third of the expected number. SNO could—and did—detect them all.

Dr. McDonald is a Companion of the Order of Canada and the holder of 12 honorary degrees. The Arthur B. McDonald Institute at Queen's University continues his legacy of fundamental research on astroparticle physics, including investigations of the detailed properties of neutrinos and the nature of dark matter. Dr. McDonald shared the 2015 Nobel Prize in Physics with Dr. Takaaki Kajita of the Japanese Super-Kamiokande experiment, which also made vital contributions to solving the solar neutrino problem.

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the neutrinos that were supposed to be produced in the Sun's core *were* being produced, but they were changing to other flavours of neutrinos on the way to Earth. Previous detectors had mainly been sensitive to a single flavour.

Not only were the SNO's total neutrino numbers in excellent agreement with those predicted by solar theories—thereby solving the solar neutrino problem—it also demonstrated that neutrinos can change flavour as they travel, which requires them to have a tiny mass. This result had far-reaching implications for many areas of astronomy, such as our understanding of dark matter, which we'll encounter later. SNO's strong confirmation of the basic correctness of models of the fusion processes in the Sun's core was a milestone accomplishment, and a good example of the interplay of theory and experiment in astrophysics. In recognition of the significance of the SNO results, the 2015 Nobel Prize for Physics was awarded to the observatory's visionary director, Arthur B. McDonald.

The Pressure–Temperature Thermostat

If stars are giant nuclear reactors, what stops the nuclear reactions from spiralling out of control and destroying the star? It turns out that a delicate balance between gas pressure and temperature acts as a solar thermostat, regulating the fusion reactions.

In a star, the energy produced by nuclear reactions generates pressure that balances the inward pull of gravity. Consider what would happen if the reactions began to produce too much energy. The extra energy flowing out of the star's core would drive up the pressure and force the star to expand. The expansion would lower the central temperature and density and consequently slow the nuclear reactions until the star returned to its original size. Thus the star has a built-in regulator that keeps the nuclear reactions from occurring too rapidly.

The same thermostat keeps the reactions from dying down. Suppose the nuclear reactions began making too little energy. Then the star would contract slightly, increasing the central temperature and density, resulting in an increase in the rate of nuclear energy generation.

The overall stability of a star depends on the relation between gas pressure and temperature. If the material of the star has the property of normal gases—for which an increase or decrease in temperature produces a corresponding change in pressure—the pressure–temperature thermostat can function properly and contribute to the stability of the star. In the next section you will see how this thermostat accounts for the relation between mass and luminosity for main-sequence stars.

7.3 Main-Sequence Stars

You can understand the deepest secrets of the stars by looking at the most obvious feature of the H–R diagram: the main sequence (see Chapter 6). Roughly 90 percent of all the stars that generate energy by nuclear fusion are main-sequence stars, and they obey a simple relationship that is the key to understanding the life and death of stars.

The Mass–Luminosity Relation

You learned in Chapter 6 that observations of the temperature and luminosity of stars show that main-sequence stars obey a simple rule: the more massive a star is, the more luminous it is. That rule is the key to understanding the stability of main-sequence stars. In fact, the mass–luminosity relation is predicted by the theories of stellar structure, giving astronomers direct observational confirmation of those theories.

To understand the mass–luminosity relation, you can consider both the law of hydrostatic equilibrium, which says that pressure balances weight, and the pressure–temperature thermostat, which regulates energy production. A star that is more massive than the Sun has more weight pressing down on its interior, so the interior must have a high pressure to balance that weight. That means the massive star's automatic pressure–temperature thermostat must keep the gas in its interior hot and the pressure high. A star less massive than the Sun has less weight on its interior. Therefore, it needs less internal pressure, and so its pressure–temperature thermostat is set lower. In other words, massive stars are more luminous because they must make more energy to support their larger weight. If they were not so luminous, they would not be stable.

Brown Dwarfs

The mass–luminosity relation also tells you why the main sequence has a lower end, a minimum mass. Objects with masses less than about 0.08 of the Sun's mass cannot raise their central temperature high enough to sustain hydrogen fusion. Called brown dwarfs, such objects are only about ten times the diameter of Earth—about the same size as Jupiter—and may still be warm from the processes of formation, but they do not generate energy by hydrogen fusion. They have contracted as much as they can and are slowly cooling off.

Brown dwarfs fall in the gap between low-mass M stars and massive planets like Jupiter. They would look dull orange or red to your eyes—which is why they are

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labelled "brown"—because they emit most of their energy in the infrared. The warmer brown dwarfs fall in spectral class L, the cooler ones in spectral class T, and the very cool ones in spectral class Y (see Chapter 6). Because they are so small and cool, brown dwarfs are very low-luminosity objects and thus difficult to find. Nevertheless, hundreds are known, and they may be as common as M stars.

The Life of a Main-Sequence Star

While a star is on the main sequence, it is stable, so you might think its life would be totally uneventful. But a main-sequence star needs to fuse hydrogen to produce the pressure necessary to balance gravity. As the star ages, it gradually uses up its hydrogen fuel and the balance between pressure and gravity starts to shift. Consequently, even the stable main-sequence stars are changing as they consume their hydrogen fuel.

Recall that hydrogen fusion combines four nuclei into one. As a main-sequence star fuses its hydrogen, the total number of particles in its interior decreases. Each newly made helium nucleus can exert only the same pressure as a hydrogen nucleus. Because the gas has fewer nuclei, its total pressure is less. This condition unbalances the gravity–pressure stability, and gravity squeezes the core of the star more tightly. As the core contracts, its temperature increases, and the nuclear reactions run faster, releasing more energy. This additional energy flowing outward forces the outer layers to expand. Therefore, as a main-sequence star slowly turns hydrogen into helium in its core, the core contracts and heats up. The extra heat released by the core drives the outer layers of the star to expand. However, because expansion cools a gas, the outer layers of the star actually cool down when the interior of the star heats up. The star becomes larger and cooler but the increase in size more than offsets the decrease in temperature and the star's luminosity actually goes up.

These gradual changes during the lifetime of main-sequence stars mean that the main sequence is not a sharp line across the H–R diagram, but rather a band. Stars begin their stable lives fusing hydrogen on the lower edge of this band, which is known as the **zero-age main sequence (ZAMS)**, but gradual changes in luminosity and surface temperature move the stars upward and slightly to the right, as shown in Figure 7.8. By the time they reach the upper edge of the main sequence, they have exhausted nearly all the hydrogen in their centres. If you precisely measure and plot the luminosity and temperature of a main-sequence star on the H–R diagram, you can estimate its age in this way.

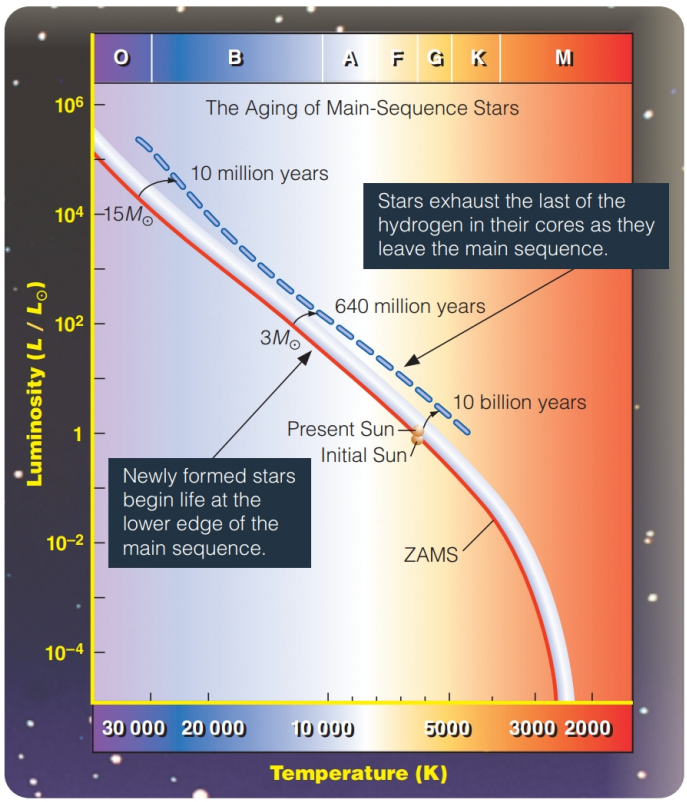


Figure 7.8 The aging of main-sequence stars. A newborn star reaches stability with properties that place it on the H–R diagram at the lower edge of the main-sequence band, along the line called the zero-age main sequence (ZAMS). As a star converts hydrogen in its core into helium, it moves slowly away from the ZAMS and across the main sequence, becoming slightly more luminous and cooler. Once a star consumes all the hydrogen in its core, it can no longer remain a stable main-sequence star. More massive stars age rapidly, but less massive stars use up the hydrogen in their cores more slowly and live longer main-sequence lives.

The Sun is a typical main-sequence star, and as it undergoes these gradual changes Earth will suffer. When the Sun began its main-sequence life about 5 billion years ago, it was only about 70 percent as luminous as it is now. By the time it leaves the main sequence in about another 5 billion years, the Sun will have twice its present luminosity. Long before that, the rising luminosity of the Sun will raise Earth's average temperature, melt the polar caps, modify Earth's climate, and ultimately boil away Earth's oceans. Life on Earth will probably not survive

zero-age main sequence (ZAMS) The location in the H–R diagram where stars first reach stability as hydrogen-burning stars.

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Table 7.2 | Main-Sequence Stars

Spectral Type	Mass (Sun = 1)	Luminosity (Sun = 1)	Approximate Years on Main Sequence
O5	40	400 000	1×10^6
B0	15	13 000	11×10^6
A0	3.5	80	440×10^6
F0	1.7	6.4	3×10^9
G0	1.1	1.4	8×10^9
K0	0.8	0.46	17×10^9
M0	0.5	0.08	56×10^9

these changes in the Sun, but humans have a billion years or more to prepare.

The average star spends 90 percent of its life on the main sequence. This explains why 90 percent of all true stars are main-sequence stars; you are most likely to see a star during that long, stable period while it is on the main sequence. The number of years a star spends on the main sequence depends on its mass (Table 7.2). Massive stars consume fuel rapidly and live short lives, but low-mass stars conserve their fuel and shine for billions of years. For example, a 25-solar-mass star will exhaust its hydrogen and die in only about 7 million years. The Sun has enough fuel to last about 10 billion years. The red dwarfs have little fuel, but they use it up very slowly and may be able to survive for 100 billion years or more. (Refer to **The Life Expectancies of Stars** in the Math Reference Cards.)

7.4 The Birth of Stars

The key to understanding star formation is the correlation between young stars, short-lived stars, and interstellar clouds of gas and dust. Young and short-lived stars are often found lighting up clouds of gas and dust (see Figure 7.9), which should lead you to suspect that stars form from such clouds.

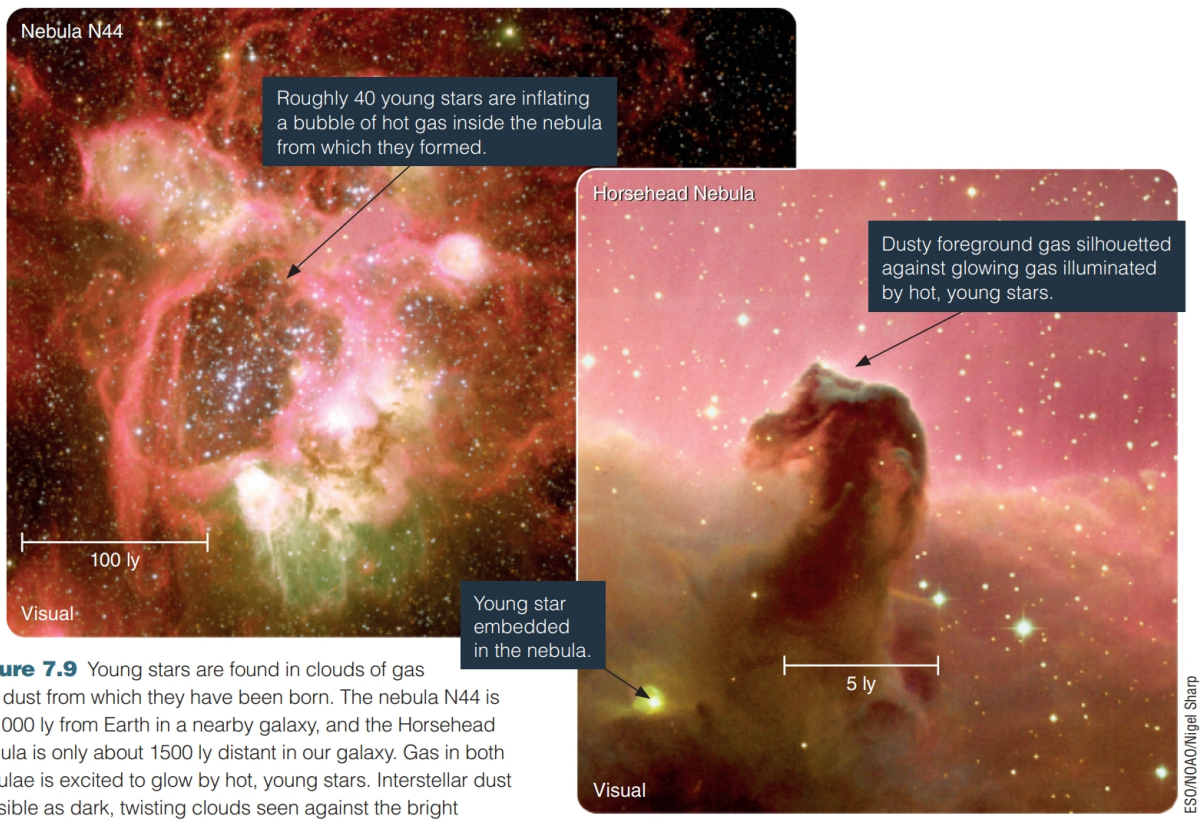


Figure 7.9 Young stars are found in clouds of gas and dust from which they have been born. The nebula N44 is 170 000 ly from Earth in a nearby galaxy, and the Horsehead Nebula is only about 1500 ly distant in our galaxy. Gas in both nebulae is excited to glow by hot, young stars. Interstellar dust is visible as dark, twisting clouds seen against the bright background gas.

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The Interstellar Medium

A common misconception is that the space between the stars is empty—a vacuum. In fact, if you glance at Orion's sword on a winter evening, you can see the Orion Nebula, a glowing cloud of interstellar gas and dust. That cloud and others are prominent examples of the low-density gas and dust between the stars, which is called the **interstellar medium (ISM)**.

About 75 percent of the mass of interstellar gas is hydrogen, and 25 percent is helium; there are also traces of carbon, nitrogen, oxygen, calcium, sodium, and heavier atoms. Notice that this is very similar to the composition of the Sun (see Chapter 5) and other stars. Roughly 1 percent of the ISM's mass is made up of microscopic particles called **interstellar dust**. The dust particles are about the size of the particles in candle smoke. The dust seems to be made mostly of carbon and silicates (rocklike minerals) mixed with or coated with frozen water, plus some organic compounds.

This interstellar material is not uniformly distributed through space; it consists of a complex tangle of cool, dense clouds pushed and twisted by currents of hot, low-density gas. Although the cool clouds contain only 10 to 1000 atoms/cm^3 (fewer than in any laboratory vacuum on Earth), astronomers refer to them as dense clouds, in contrast to the hot, low-density gas that fills the spaces between clouds. That thin gas contains only about 0.1 atom/cm^3.

How do we know the properties of the interstellar medium? As you just learned, the ISM is in some cases easily visible as clouds of gas and dust—as in, for example, the Orion Nebula. **Nebula** is the Latin word for "cloud." Such nebulae (plural) give clear evidence of an interstellar medium. Study **Visualizing Astronomy 7.1, Three Kinds of Nebulae**, and notice three important points:

1. Very hot stars can excite clouds of gas and dust to emit light, and the spectrum of this light reveals that these clouds contain mostly hydrogen gas at very low densities.
2. Where dusty clouds reflect the light of stars, you see evidence that the dust in the clouds is made up of very small particles.
3. Some dense clouds of gas and dust are dark and therefore detectable in visible light only where they are silhouetted against background regions filled with stars or bright nebulae.

If a cloud is less dense, starlight may be able to penetrate it, but the stars look dimmer because the dust in the cloud scatters some of their light. Dust particles scatter shorter wavelengths more easily than longer ones, so the bluer photons tend to be scattered while the redder ones make it through the cloud. For this reason, stars viewed through dusty clouds in the ISM look redder than they should for their respective spectral types. This effect is called **interstellar reddening**, as illustrated in Figure 7.10. The same physical process makes the setting Sun look red. The fact that distant stars are dimmed and reddened by intervening gas and dust is clear evidence of an interstellar medium.

Astronomers study the ISM not just by considering the light it scatters, but also by examining the light it *emits*. The denser parts of the interstellar medium consist of extremely cold gas and dust, with temperatures between about 10 and 50 K. How do we know this? You learned in Chapter 6 that dense objects, such as stars and planets, produce a special type of continuous spectrum called a blackbody spectrum. Although particles of interstellar dust are very tiny, they are also dense, so they also produce a blackbody spectrum. However, because the ISM dust particles are much colder than stars, their blackbody spectra peak at much longer wavelengths. So, interstellar dust grains emit most of their light in the far-infrared part of the spectrum, and are dark when viewed in visible light. Using infrared space telescopes such as the Herschel Space Observatory, we can gather the light from these cold dust particles, measure their spectra, and determine their temperatures. Figure 7.11 shows a far-infrared image of the dust in one of these clouds.

We can begin to piece together the full story of how stars form by examining a single star-forming region in multiple wavelengths of light. Figure 7.12 shows the famous 30 Doradus star-forming complex, also known as the Tarantula Nebula. Young massive stars in this nebula are glowing very brightly, emitting intense X-ray radiation and streams of high-energy particles that are driving away the gas and dust around them. Meanwhile, the cooler gas and dust continues to collapse in pockets here and there to form new stars. The mass–luminosity relationship tells us that massive stars have short lives, lasting only a few million years. Finding short-lived massive stars deeply embedded in clouds of cool gas and dust gives us high confidence that these stars actually formed from the material in these clouds.

interstellar medium (ISM) The gas and dust distributed between the stars.

interstellar dust Microscopic solid grains in the interstellar medium.

nebula A relatively dense cloud of interstellar gas and dust.

interstellar reddening The process in which dust scatters blue light out of starlight and makes the stars look redder.

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Visualizing Astronomy 7.1
Three Kinds of Nebulae

1

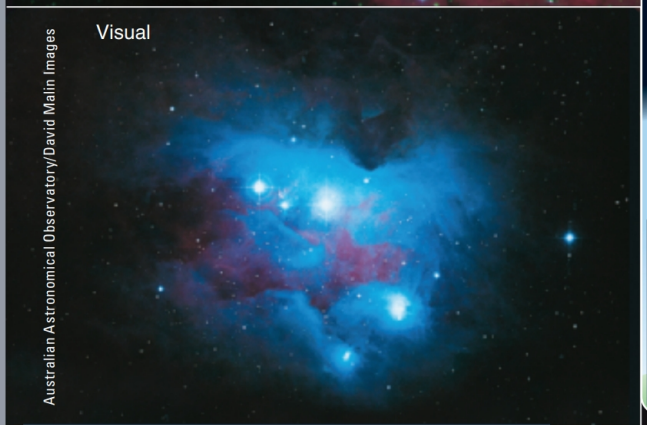
Emission nebulae are produced when a hot star excites the gas near it to produce an emission spectrum. The star must be hotter than about spectral type B1 (25 000 K). Cooler stars do not emit enough ultraviolet radiation to ionize the gas. Emission nebulae have a distinctive pink colour produced by the blending of the red, blue, and violet Balmer lines. Emission nebulae are also called **H II regions**, following the convention of using Roman numerals to indicate an atom's ionization state. Thus, H I means neutral hydrogen; H II is ionized.

In an H II region, the ionized nuclei and free electrons are mixed. When a nucleus captures an electron, the electron falls down through the atomic energy levels, emitting photons at specific wavelengths. Spectra indicate that the nebulae have compositions much like that of the Sun—mostly hydrogen. Emission nebulae have densities of 100 to 1000 atoms per cubic centimetre, thinner than the best vacuums produced in laboratories on Earth.

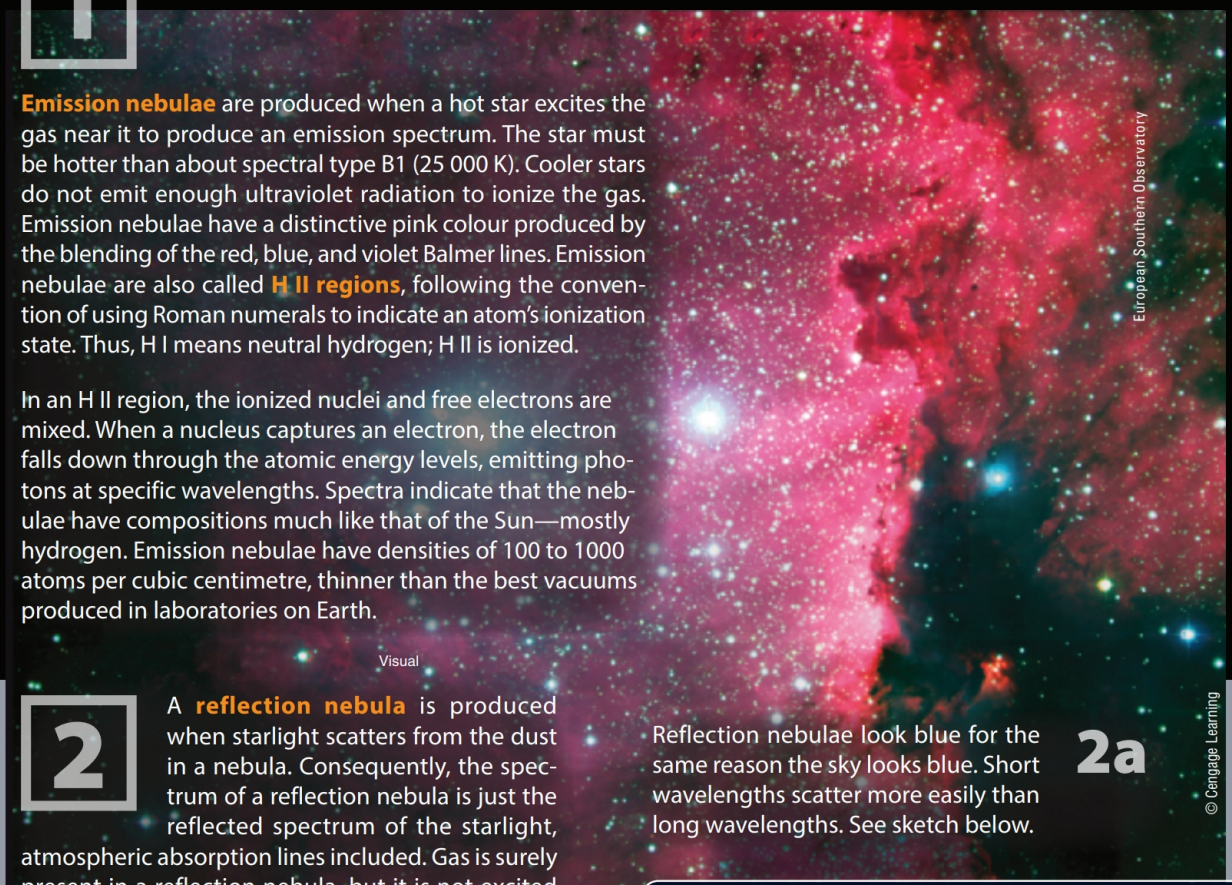
Visual

2

A **reflection nebula** is produced when starlight scatters from the dust in a nebula. Consequently, the spectrum of a reflection nebula is just the reflected spectrum of the starlight, atmospheric absorption lines included. Gas is surely present in a reflection nebula, but it is not excited enough to emit photons. See image below.

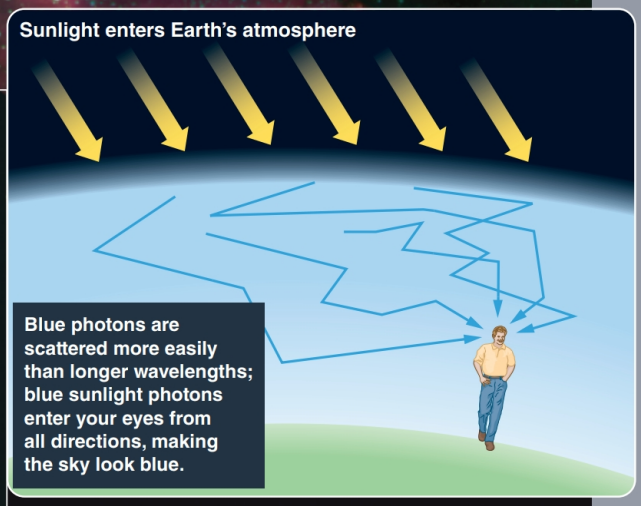


Reflection nebulae NGC 1973, 1975, and 1977 are just north of the Orion Nebula. The pink glow from ionized hydrogen is an emission nebula deep inside the complex of reflection nebulae.



Reflection nebulae look blue for the same reason the sky looks blue. Short wavelengths scatter more easily than long wavelengths. See sketch below.

2a

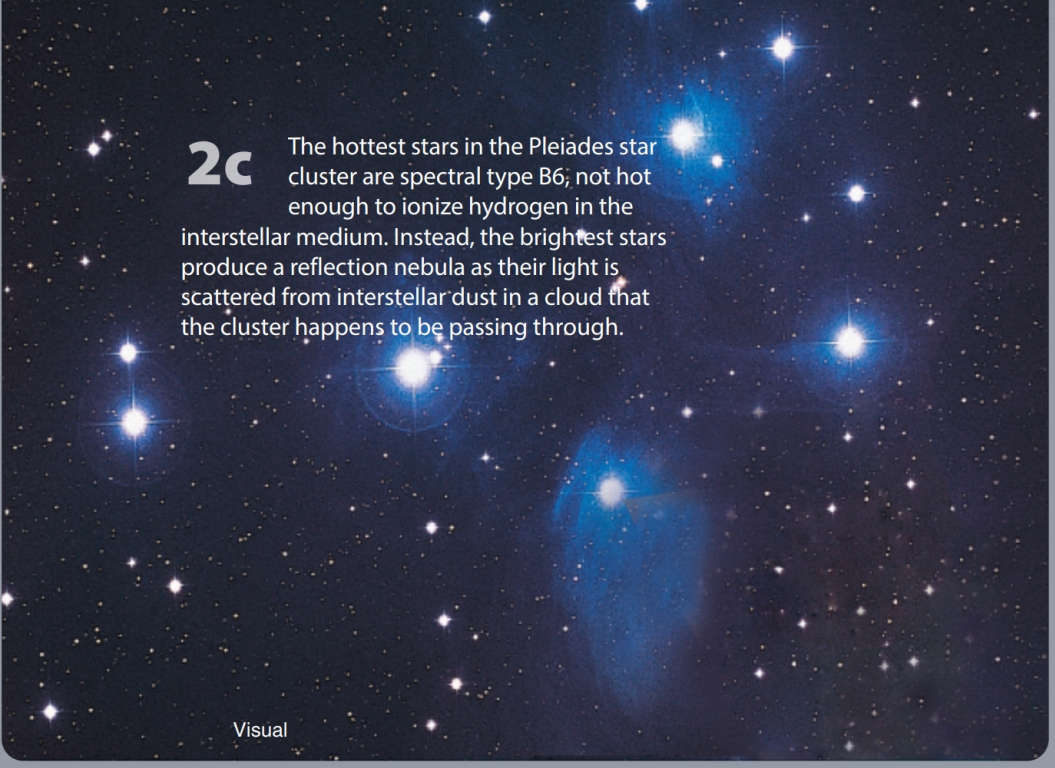


The blue colour of reflection nebulae at left shows that the dust particles must be very small to preferentially scatter the blue photons. Interstellar dust grains must have typical diameters ranging from about 10 to 1000 nm (0.01 to 1 micron). This particular reflection nebula includes an emission nebula.

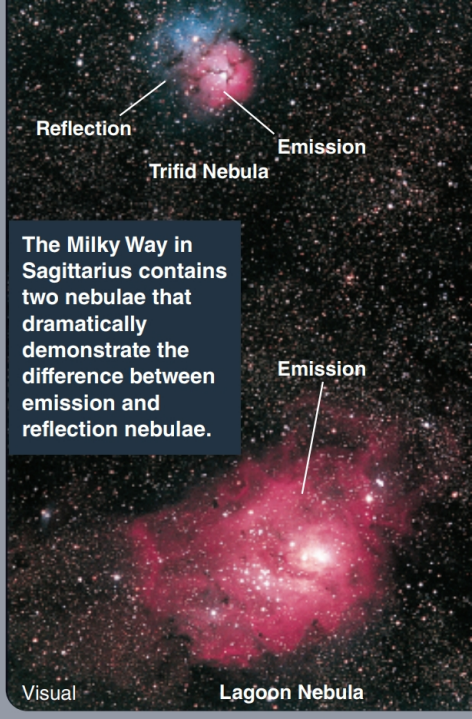
2b

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2c The hottest stars in the Pleiades star cluster are spectral type B6, not hot enough to ionize hydrogen in the interstellar medium. Instead, the brightest stars produce a reflection nebula as their light is scattered from interstellar dust in a cloud that the cluster happens to be passing through.



Australian Astronomical Observatory/David Malin Images

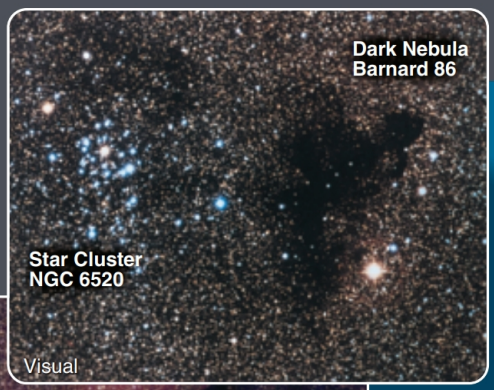


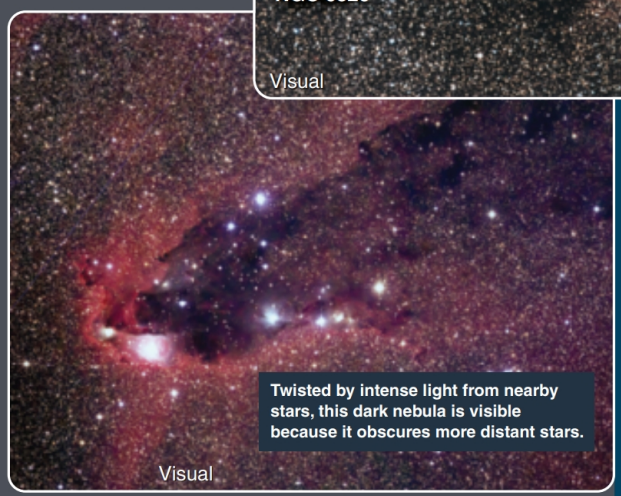
The Milky Way in Sagittarius contains two nebulae that dramatically demonstrate the difference between emission and reflection nebulae.

Daniel C. Good

Dark nebulae are clouds of gas and dust dense enough to obstruct the view of more distant stars. Their shapes, as shown at left and lower left, are generally irregular, suggesting that, in addition to the effects of nearby stars, there are breezes and currents pushing through the interstellar medium.

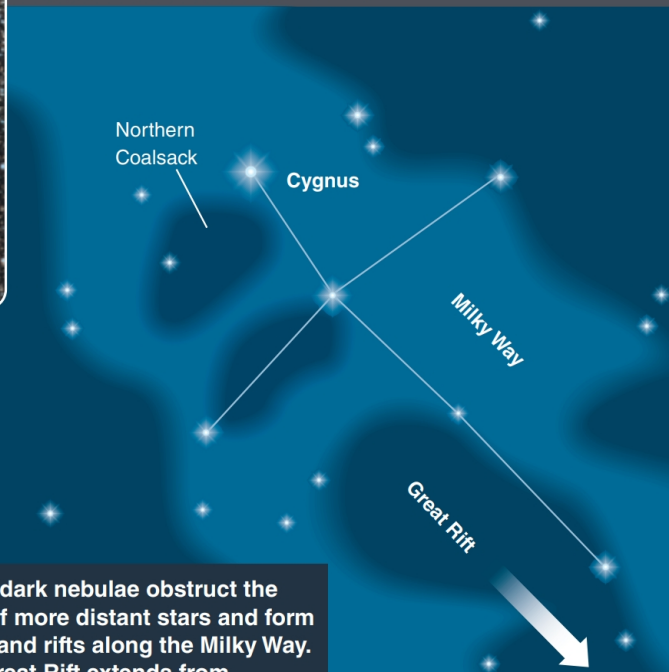
3





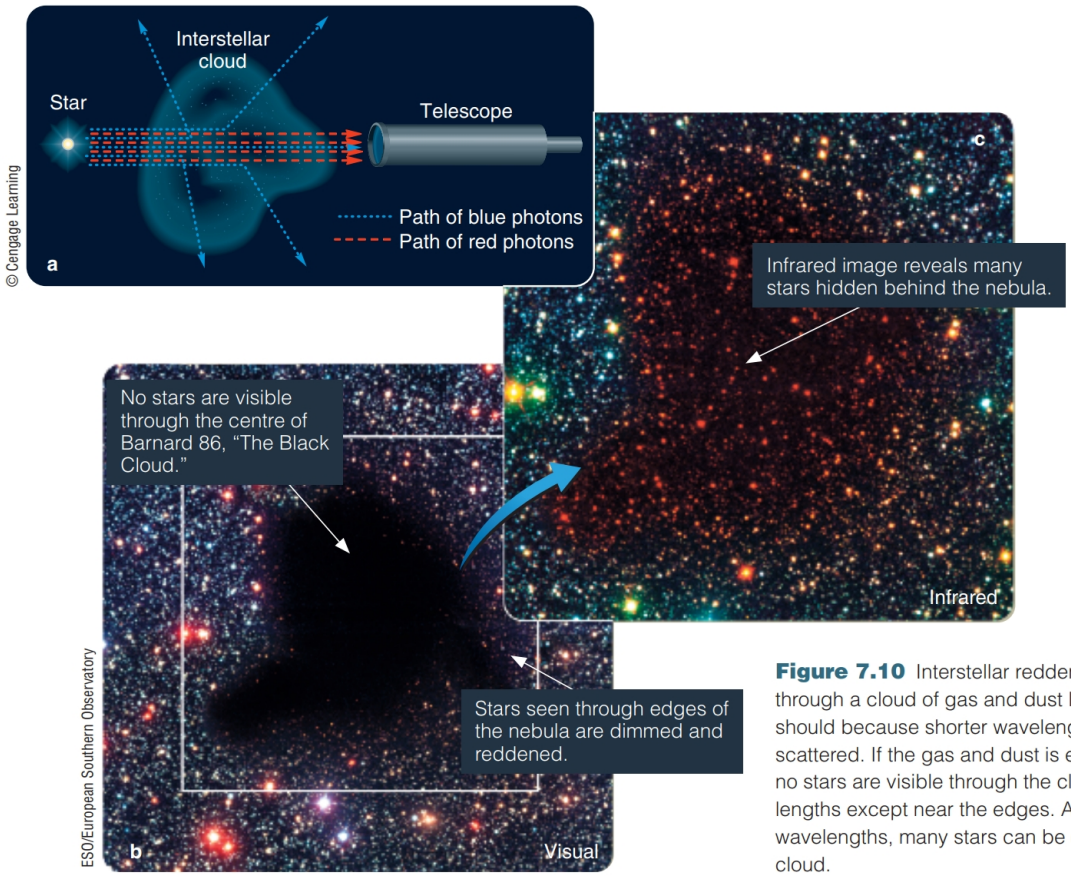
Twisted by intense light from nearby stars, this dark nebula is visible because it obscures more distant stars.

Australian Astronomical Observatory/David Malin Images



Large dark nebulae obstruct the view of more distant stars and form holes and rifts along the Milky Way. The Great Rift extends from Cygnus to Sagittarius.

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ESO/European Southern Observatory

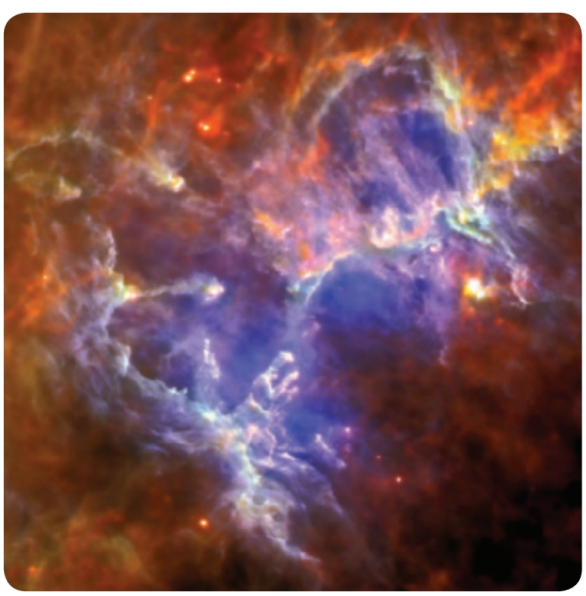
Figure 7.10 Interstellar reddening makes stars seen through a cloud of gas and dust look redder than they should because shorter wavelengths are more easily scattered. If the gas and dust is especially dense, no stars are visible through the cloud at visual wavelengths except near the edges. At longer near-infrared wavelengths, many stars can be detected behind the cloud.

The Formation of Stars from the Interstellar Medium

Our understanding of how stars form derives from a combination of observations and theories. The theory of gravity predicts that the combined gravitational attraction of the atoms in a cloud of gas will shrink the cloud, pulling every atom toward the centre. That might lead you to expect that every cloud would eventually collapse and become a star; however, the thermal energy in the cloud resists collapse. Interstellar clouds are very cold, but even at a temperature of only 10 K the average hydrogen atom moves at about 0.33 km/s. That much thermal motion would make the cloud drift apart if gravity were too weak to hold it together.

Other factors can help a cloud resist its own gravity. Observations show that clouds are turbulent, with currents of gas pushing through and colliding with each other. Magnetic fields threading these clouds resist being squeezed. The support provided by these factors means that only the densest clouds are likely to contract.

The densest interstellar clouds contain from 10^3 to 10^5 atoms/cm^3 and have temperatures as low as 10 K.



Far-infrared: ESA/Herschel/PACS/SPIRE/Hill, Motte, HOBYS Key Programme Consortium; X-ray: ESA/XMM-Newton/EPIC/XMM-Newton-SOC/Boulanger, CC BY-SA 3.0 IGO

Figure 7.11 Far-infrared image of the famous Eagle Nebula, a star-forming cloud in the interstellar medium. This false-colour image, taken with the Herschel Space Observatory, shows the light emitted by dust grains. The red colour shows dust with a temperature around 10 K, while the blue shows dust at about 40 K.

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X-ray: NASA/CXC/PSU/L.Townsley et al.; Infrared: NASA/JPL/PSU/L.Townsley et al.

Figure 7.12 This image of the 30 Doradus star-forming cloud combines both X-rays (blue) from the Chandra X-ray Observatory and infrared light (orange) from the Spitzer Space Telescope. The infrared light indicates the presence of cold dust only tens of degrees above absolute zero. The X-rays indicate the presence of hot gas with temperatures in the millions of degrees. The gas is heated to these tremendous temperatures partly by the explosive deaths of short-lived massive stars that formed within the cloud.

The masses of these clouds range from a few hundred thousand to a few million solar masses. In such dense clouds, where collisions among atoms are more likely and the cloud shields itself from high-energy photons coming from outside, hydrogen can exist as molecules (H_2) rather than as atoms. These densest parts of the ISM are called **molecular clouds**, and the largest are called giant molecular clouds. Measurements of the distribution and motions of these gases reveal that stars form inside molecular clouds when the densest parts of the clouds become unstable and contract under the influence of their own gravity.

Most clouds do not appear to be gravitationally unstable and do not contract to form stars on their own. However, a stable cloud colliding with a **shock wave** (the astronomical equivalent of a sonic boom) can be compressed and disrupted into fragments. Theoretical calculations show that some of these fragments can become dense enough to collapse under the influence of their own gravity and form stars (Figure 7.13).

Supernova explosions—exploding stars—produce shock waves that compress the interstellar medium. Recent observations show young stars forming at the edges of such shock waves. Another source of shock waves may be the birth of very hot stars, as shown in Figure 7.12. Even the collision of two interstellar clouds can produce a shock wave that compresses nearby gas and triggers star formation. Some of these processes are shown in Figure 7.14.

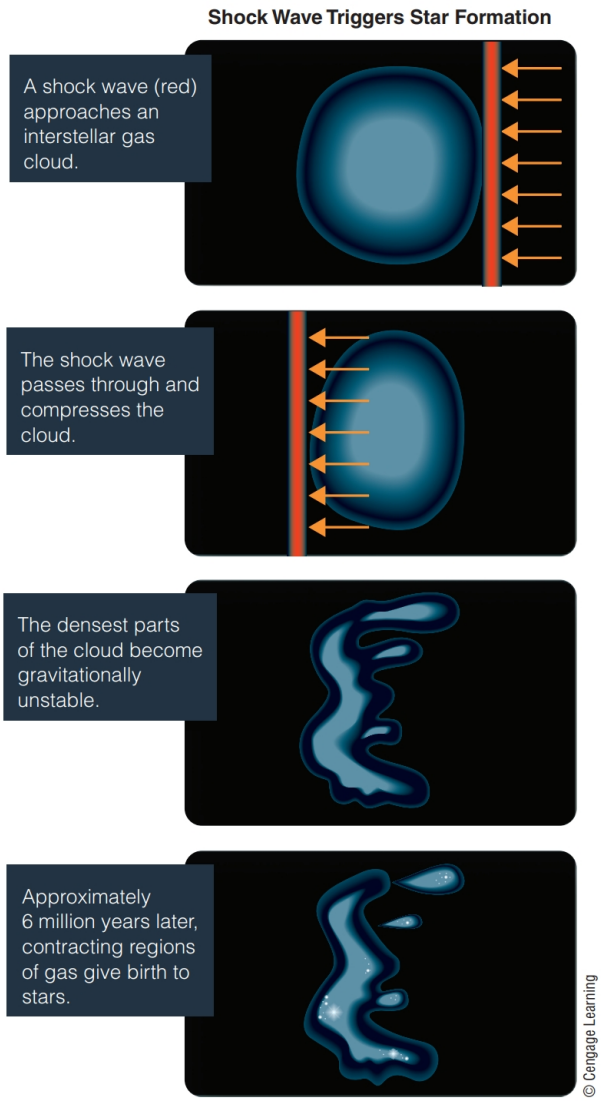


Figure 7.13 Shock wave triggers star formation.

Although these are important sources of shock waves, the dominant trigger of star formation in our galaxy may be the spiral pattern of its arms, which you learned in Chapter 1. As interstellar clouds encounter these spiral arms, the clouds become compressed, and star formation can be triggered (see Chapter 9).

molecular cloud A dense interstellar gas cloud in which atoms are able to link together to form molecules such as H_2 and CO.

shock wave A sudden change in pressure that travels as an intense sound wave.

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Figure 7.14 (a) The blast of visible and ultraviolet light from an earlier generation of massive stars has compressed neighbouring gas and triggered the formation of more stars. Those stars are now triggering the birth of a third generation. (b) The explosion of a supernova a few million years ago produced a shock wave that is triggering star formation where it slams into nearby clouds of gas and dust.

Once begun, star formation can spread like a grass fire. Both high-mass and low-mass stars form together, but when the massive stars form, their intense radiation or eventual supernova explosions compress the surrounding gas. This compression in turn can trigger the formation of more stars, some of which will be massive. Thus, a few massive stars can drive a continuing cycle of star formation in a giant molecular cloud.

A collapsing molecular cloud does not usually form a single star; because of instabilities, the cloud typically breaks into fragments, producing perhaps thousands of stars. A stable group of stars that formed and are held together by their combined gravity is called a **star cluster**. In contrast, a **stellar association** is a group of stars that formed together but are not gravitationally bound to one another. The stars in an association drift away from each other in a few million years. The youngest associations are rich in young stars, including O and B stars. O and B stars have lifetimes so short in astronomical terms (Table 7.2) that they never have a chance to stray far from their birthplaces; these stars serve as signposts of star-forming regions.

star cluster A group of stars that formed together and orbit a common centre of mass.

stellar association A group of stars that formed together but are not gravitationally bound to one another.

protostar A collapsing cloud of gas and dust destined to become a star.

The Formation of Protostars

You might be wondering how the unimaginably cold gas of an interstellar cloud can heat up to form a star. The answer is gravity.

Once part of a cloud is triggered to collapse, gravity draws each atom toward the centre. As the atoms fall inward, they collide with one another. The collisions convert inward velocities into faster and faster random velocities. Remember that temperature is a measure of the random velocities of the atoms in a gas. Thus, as the cloud collapses, the temperature of the gas goes up.

The initial collapse of the cloud forms a dense core of gas. As more gas falls in, a warm **protostar** develops, buried deep in the dusty gas cloud. The cloud continues to contract, although much more slowly than if it were collapsing in free-fall under its own gravity. A protostar is an object that will eventually become a star. Theory predicts that protostars are luminous red objects larger than main-sequence stars, with temperatures ranging from a few hundred to a few thousand degrees Kelvin.

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As the protostar collapses under its own gravity, its atoms move ever faster, thereby converting gravitational potential energy into thermal energy. Half of this thermal energy radiates into space, but the remaining half is trapped. As the internal temperature climbs, the gas of the protostar becomes ionized, changing into a mixture of positively charged atomic nuclei and free electrons. When the centre gets hot enough, nuclear fusion reactions begin generating enough energy to replace the radiation escaping from the surface of the star. The protostar then halts its contraction and becomes a stable, main-sequence star.

The time a protostar takes to contract from a cool interstellar gas cloud to a main-sequence star depends on its mass. The more massive the star, the stronger its gravity and the faster it contracts. The Sun took about 30 million years to pass through the protostar stage and reach the main sequence, but a 15-solar-mass star can contract in only 100 000 years. Conversely, a 0.2-solar-mass star takes 1 billion years to reach the main sequence.

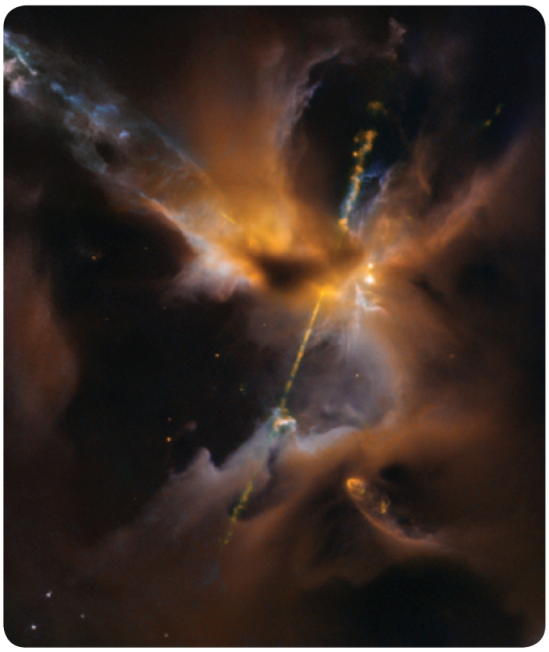
Observations of Star Formation

We have described a model for how stars form. But scientific models must be tested by comparing them with evidence. What's the evidence for the model of star formation?

Catching stars in the act of forming is difficult. The protostar stage is predicted to last less than 0.1 percent of a star's total lifetime, so protostars are rare in comparison to main-sequence stars. Furthermore, protostars form deep inside clouds of dusty gas that absorb most of the light the protostar is emitting. Fortunately, as we have discussed, longer wavelengths of light easily penetrate interstellar dust and gas, so observations at infrared and radio wavelengths make it possible to directly study the earliest phases of star formation.

Bok globules are small, very dense knots of gas and dust within larger nebulae. These globules probably represent the very first stages of star formation. You've already seen one of the best studied Bok globules (refer to Figure 7.10). Most of these globules spin very slowly, but their rate of spin accelerates as they collapse. Eventually, their spin flattens them out into a disk, like spinning pizza dough. Material flowing through the disk onto the protostar is sometimes violently flung outward along the star's rotational poles, forming spectacular protostellar jets, as shown in Figure 7.15. These short-lived displays are called **Herbig–Haro objects**.

Star-forming molecular clouds contain many stars with temperatures and luminosities that correspond to model predictions of the properties of very young stars. These include **T Tauri stars**, which are protostars with about the mass of the Sun that show signs of active chromospheres—as you might expect from young rapidly rotating stars with strong magnetic dynamos (see Chapter 5). T Tauri stars are also often surrounded by thick disks of gas and dust that are very bright at infrared wavelengths.



NASA and ESA; Acknowledgment: NASA, ESA, the Hubble Heritage (STScI/AURA)/Hubble-Europe (ESA) Collaboration, D. Padgett (GSFC), T. Megeath (University of Toledo), and B. Reipurth (University of Hawaii)

Figure 7.15 Infrared image of the Herbig–Haro object HH 24, a protostar that is launching twin jets of gas about half a light-year long into the surrounding dusty molecular cloud. Dust mostly obscures the protostar itself, but the jets are prominently visible as thin lines running from upper right to lower left.

Although star formation still holds many puzzles, the general process seems clear: interstellar gas clouds are compressed by external forces to the point where their own gravity can take over and crush them, then they heat up to form protostars and eventually main-sequence stars.

The Orion Nebula

On a clear winter night you can see the Orion Nebula as a fuzzy wisp in Orion's sword, even with your unaided eye. With binoculars or a small telescope what you see is striking, and through a large telescope it is breathtaking. At the centre of the nebula lie four brilliant blue-white stars known as the Trapezium, the brightest of a cluster of a few hundred stars. Surrounding the stars are the glowing filaments of a nebula more

Bok globule Small, dark cloud only about 1 ly in diameter that contains 10 to 1000 solar masses of gas and dust, thought to be related to star formation.

Herbig–Haro object A small nebula that varies irregularly in brightness, produced when protostellar jets slam into the surrounding ISM.

T Tauri star A young star surrounded by gas and dust, understood to be contracting toward the main sequence.

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Visualizing Astronomy 7.2

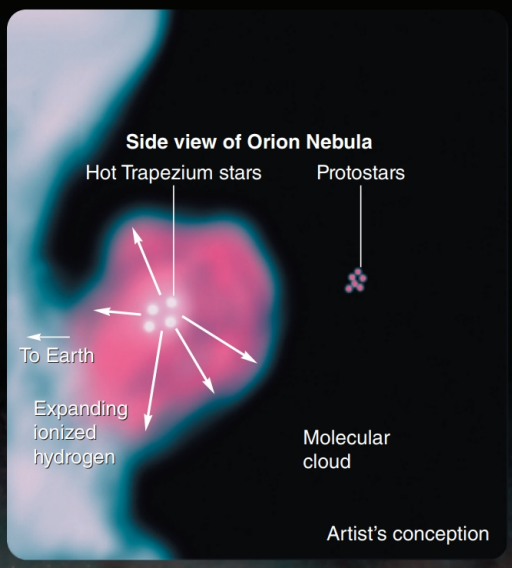
Star Formation in the Orion Nebula

1

The visible Orion Nebula shown below is a pocket of ionized gas on the near side of a vast, dusty molecular cloud that fills much of the southern part of the constellation Orion. The molecular cloud can be mapped by radio telescopes. To scale, the cloud would be many times larger than this page. As the stars of the Trapezium were born in the cloud, their radiation has ionized the gas and pushed it away. Where the expanding nebula pushes into the larger molecular cloud, it is compressing the gas (see diagram at right) and may be triggering the formation of the protostars that can be detected at infrared wavelengths within the molecular cloud.

Hundreds of stars lie within the nebula, but only the four brightest, those in the Trapezium, are easy to see with a small telescope. A fifth star, at the narrow end of the Trapezium, can be visible on nights of good seeing.

The cluster of stars in the nebula is less than 2 million years old. This means the nebula is similarly young.





NASA/JPL-Caltech/n.Flagey & A. Noriega-Crespo

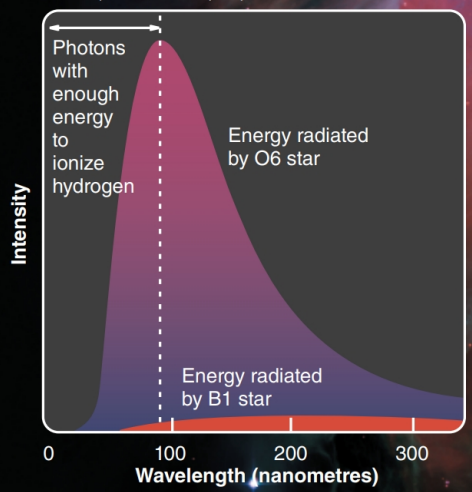
The near-infrared image above reveals more than 50 low-mass, cool protostars.



NASA/JPL-Caltech/Univ. of Toledo/NOAO

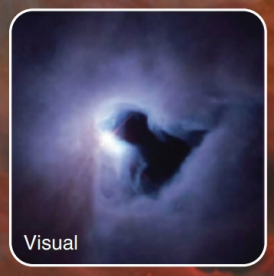
Visual

NASA, ESA, M. Robberto, STScI and the Hubble Space Telescope Orion Treasury Project Team



2

Of all the stars in the Orion Nebula, just one is hot enough to ionize the gas. Only photons with wavelengths shorter than 91.2 nm can ionize hydrogen. The second-hottest stars in the nebula are B1 stars, and they emit little of this ionizing radiation. The hottest star, however, is an O6 star that has 30 times the mass of the Sun. At a temperature of 40 000 K, it emits plenty of photons with wavelengths short enough to ionize hydrogen. Remove that one star, and the nebula's emission would turn off.

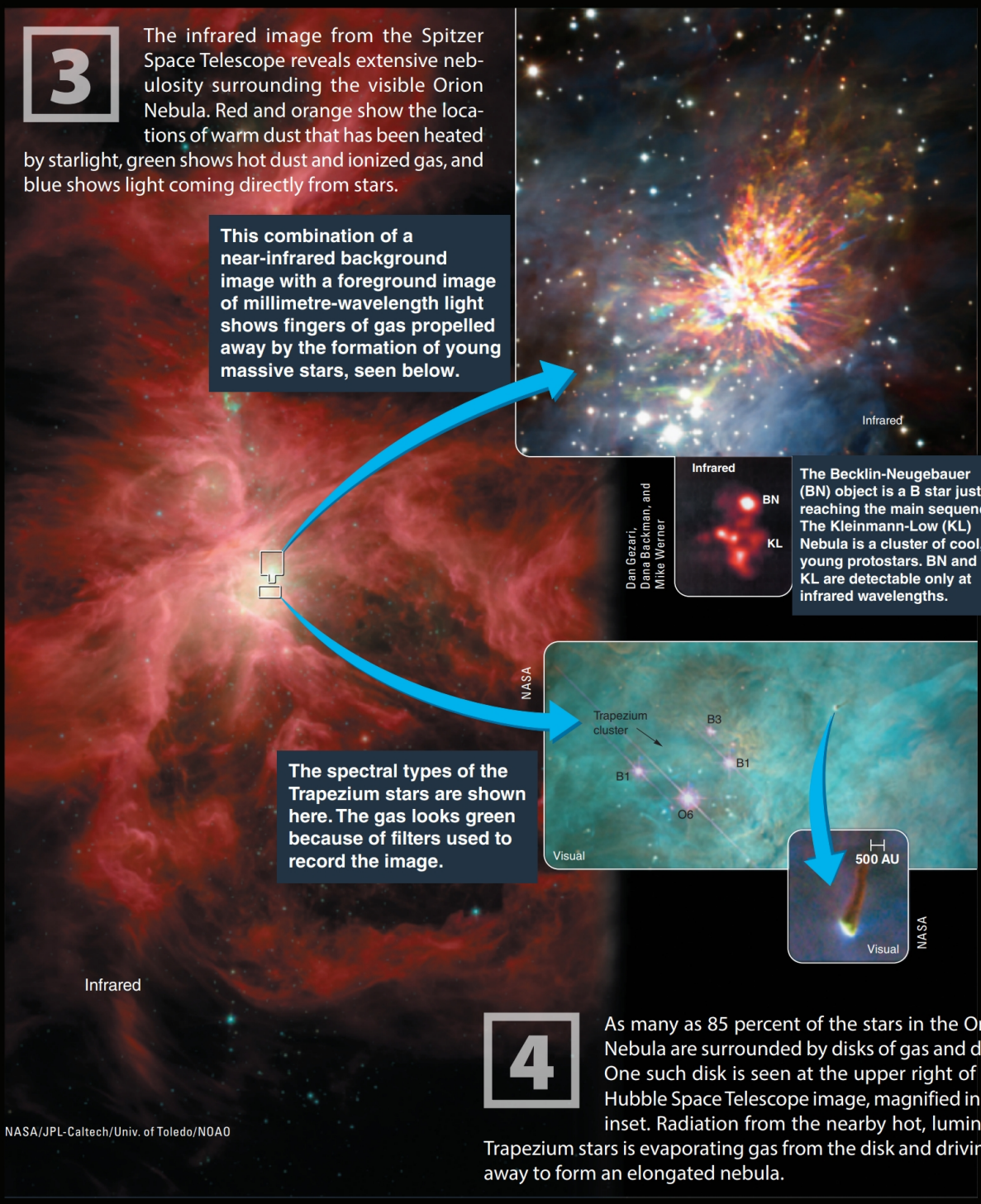


NASA and The Hubble Heritage Team (STScI)

Small dark clouds called Bok globules, named after astronomer Bart Bok, are found in and near star-forming regions. The one pictured here is part of nebula NGC 1999 near the Orion Nebula. Typically about 1 light-year in diameter, they contain from 10 to 1000 solar masses.

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3
The infrared image from the Spitzer Space Telescope reveals extensive nebulosity surrounding the visible Orion Nebula. Red and orange show the locations of warm dust that has been heated by starlight, green shows hot dust and ionized gas, and blue shows light coming directly from stars.
This combination of a near-infrared background image with a foreground image of millimetre-wavelength light shows fingers of gas propelled away by the formation of young massive stars, seen below.
Infrared
ALMA (ESO/NAOJ/NRAO), J. Bally/H. Drass et al.
Infrared
BN
KL
Dan Gezari, Dana Backman, and Mike Werner
The Becklin-Neugebauer (BN) object is a B star just reaching the main sequence. The Kleinmann-Low (KL) Nebula is a cluster of cool, young protostars. BN and KL are detectable only at infrared wavelengths.
NASA
Trapezium cluster
B3
B1
B1
O6
Visual
The spectral types of the Trapezium stars are shown here. The gas looks green because of filters used to record the image.
500 AU
Visual
NASA
Infrared
NASA/JPL-Caltech/Univ. of Toledo/NOAO
4
As many as 85 percent of the stars in the Orion Nebula are surrounded by disks of gas and dust. One such disk is seen at the upper right of this Hubble Space Telescope image, magnified in the inset. Radiation from the nearby hot, luminous Trapezium stars is evaporating gas from the disk and driving it away to form an elongated nebula.

than 25 ly across. Like a great thundercloud illuminated from within, the churning currents of gas and dust suggest immense power. The significance of the Orion Nebula lies hidden, figuratively and literally, beyond the visible nebula.

Evidence of Young Stars

You should not be surprised to find star formation in Orion. The constellation is a brilliant landmark in the winter sky because it is marked by hot blue stars. These stars are bright not because they are close to Earth but because they are tremendously luminous. These O and B stars cannot live more than a few million years, so you can conclude that they must have been born recently in astronomical terms, near where they are seen now. Furthermore, the constellation contains large numbers of T Tauri stars, which are known to be young. Orion is rich with young stars.

The history of star formation in the constellation of Orion is written in its stars. The stars at Orion's west shoulder are about 12 million years old, whereas the stars of Orion's belt are about 8 million years old. The stars of the Trapezium at the centre of the nebula are no older than 2 million years. Apparently, star formation began near the west shoulder, and the massive stars that formed there triggered the formation of the stars you see in Orion's belt. That star formation may have triggered the formation of the stars you see in the nebula itself. Like a grass fire, star formation has swept across Orion from northwest to southeast.

Study **Visualizing Astronomy 7.2, Star Formation in the Orion Nebula**, and notice four points:

1. The nebula you see is only a small part of a vast, dusty molecular cloud. You see the nebula because the larger stars born within it have ionized the nearby gas and driven it outward, breaking out of the much larger molecular cloud.
2. A single very hot and short-lived O star is almost entirely responsible for ionizing the gas and making the nebula glow. This massive star has already become a main-sequence star, while its smaller siblings are still protostars.
3. Infrared observations reveal ongoing star formation deep in the molecular cloud behind the visible nebula.
4. Finally, notice that many stars visible in the Orion Nebula are surrounded by disks of gas and dust. Such disks do not last long and are clear evidence that the stars are very young.

Make special note of these disks surrounding young stars, because planets may form in them. In Chapter 12 you will study how our solar system formed in the disk of gas and dust that encircled the young Sun.

The **Big Picture**

In this chapter you learned how stars form in the very cold interstellar medium where gravity, the weakest force, works unrelentingly, gathering molecular hydrogen in tight, dense balls with sufficiently high temperatures to make stars. Our own star, the Sun, uses the proton–proton chain to convert mass into energy. Life on Earth depends on this energy, and discovering its source has helped us understand a key part of our place in the cosmos. Studying the world by comparing observations to mathematical models is a powerful tool for understanding nature, but it's not the only way people try to make sense of the cosmos.

Indigenous people have been studying the skies for thousands of years. There are hundreds of different First Nations in Canada, and each Nation has its own stories and knowledge about the sky. Much of this knowledge has been lost through colonization, but many people are struggling to relearn this knowledge. One such story, told by the Tlingit people of coastal British Columbia and southeastern Alaska, concerns Raven and the Box of Daylight. According to one version of the story, a long time ago, the world was totally dark because the Sun, Moon, and stars were kept in boxes by a great Chief. Raven, a powerful figure in many indigenous cultures, wanted to free the Sun, so he transformed himself into a hemlock needle and fell into the drinking glass of the chief's daughter. She drank him down and he grew into a child inside her. When Raven was born as the Chief's grandson, he was loved dearly and given whatever he asked for. He demanded the box of stars and cried until he got it, then threw the box and all its stars into the sky. He did the same with the Moon. Finally, when he got the box containing the Sun, he showed it to the people and asked if they would like to have light. They were so terrified when he opened the box and let out the Sun that they scattered, which is why Raven's people are found everywhere.

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Science is one way we make sense of the world. Indigenous knowledge is another. The story of Raven and the Box of Daylight highlights the connections between us, the Sun, and the energy the Sun provides. Knowing that stars are not eternal, that they are born, live, and die helps us contextualize our own place in the cosmos.

Review and Discussion Questions

Review Questions

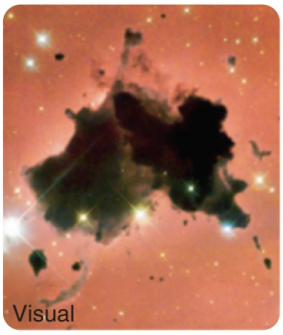
1. Describe the principle of hydrostatic equilibrium as it relates to the internal structure of a star.
2. What are the main inputs and products of the proton–proton chain? What happens to the different products?
3. How does the pressure–temperature thermostat control the nuclear reactions inside stars?
4. Step by step, explain how energy flows from the centre of the Sun out into space.
5. Why is there a mass–luminosity relation?
6. Why is there a lower limit to the mass of a main-sequence star?
7. Why does a star's life expectancy depend on its mass?
8. Why do distant stars look redder than their spectral types suggest?
9. What evidence can you cite that the interstellar medium contains both gas and dust?
10. How is the blue colour of a reflection nebula related to the blue colour of the daytime sky?
11. What factors resist the contraction of a molecular cloud?
12. How can a molecular cloud be triggered to form stars?
13. How does the contraction of a gas cloud increase its temperature?
14. Given that stars form in dense clouds of dust and gas that are opaque to visible light, what evidence can we use to test our theories of star formation?
15. What evidence is there that (a) star formation has occurred recently? (b) protostars really exist? (c) the Orion region is actively forming stars?
16. **How Do We Know?** How can mathematical models help you understand natural processes that occur in locations or with time scales that make them impossible to observe directly?

Discussion Questions

1. How does hydrostatic equilibrium relate to hot-air ballooning?
2. When you see distant streetlights through smog, they look dimmer and redder than they do normally. But when you see the same streetlights through fog or falling snow, they look dimmer, but not redder. Use your knowledge of the interstellar medium to discuss the relative sizes of the particles in smog, fog, and snowstorms compared to the wavelength of light.
3. If you could see a few stars through a dark nebula, how would you expect their spectra and colours to differ from similar stars just in front of the dark nebula?
4. Ancient astronomers, philosophers, and poets assumed that the stars were eternal and unchanging. Is there any observation they could have made or any line of reasoning that could have led them to conclude that stars don't live forever?

Learning to Look

The accompanying photo shows a dark globule of dusty gas. What do you think might be going on inside this globule? What would it look like if you could see it from the other side?



NASA and the Hubble Heritage Team, STScI/AURA

STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *The Structure and Formation of Stars.*

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
- Interactive Quizzing
- Animations
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PART TWO

8 The Deaths of Stars



Credit: CFHT/Coelum - J.-C. Cuillandre & G. Anselmi

CHAPTER OUTLINE

8.1 The Beginning of the End
8.2 The Final End of a Low-Mass Star
8.3 The Evolution of Binary Systems
8.4 The Deaths of Massive Stars
8.5 Neutron Stars
8.6 Black Holes and Relativity
8.7 Gravitational Waves

GUIDEPOST

You are beginning to understand stars. The preceding chapter described how stars are born from clouds of gas and dust in the interstellar medium and how nuclear fusion maintains high temperatures and pressures inside stars, which keeps them from collapsing under the influence of their own gravity. In this chapter you will learn what happens when a star runs out of fuel, what kind of "corpse" is left after its death, and how both of these conditions depend on its mass.

You also will learn the surprising fact that, if stars didn't die, you would not exist. When the universe began, it didn't contain most of the chemical elements of which planets and people are made. Those were formed in stars and scattered into the cosmos when those stars died. By understanding the deaths of stars, you can better understand your role in the evolution of the universe.

As you consider the fates of the stars, you will find answers to six important questions:

- What happens to a star when it uses up the last of the hydrogen fuel in its core?

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In about 5 billion years the Sun will exhaust its nuclear fuel and die, becoming a planetary nebula similar to the Helix Nebula.

The black holes of nature are the most perfect macroscopic objects there are in the universe: the only elements in their construction are our concepts of space and time.

Subrahmanyan Chandrasekhar, astrophysicist and Nobel laureate

We are made out of stardust. The iron in the hemoglobin molecules in the blood in your right hand came from a star that blew up 8 billion years ago. The iron in your left hand came from another star.

Jill Tarter, astronomer

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- What is the evidence that stars really evolve?
- What happens if an evolving star is in a binary star system?
- What can be left behind after a star dies?
- How does theory predict the existence of neutron stars and black holes?
- What is the evidence that neutron stars and black holes really exist?

This chapter ends the story of individual stars, but it does not end the story of stars. In the next chapter, you will begin exploring the giant communities in which stars live: the galaxies.

Gravity is patient—so patient it can kill stars. Astronomers occasionally see what seems to be a new star in the sky that grows brighter and then fades away after a few weeks or a year. You will discover that a **nova**, an apparently new star in the sky, is produced by an eruption on a stellar remnant, and that a **supernova**, a particularly luminous and long-lasting nova, is caused by the violent explosive death of a star. Modern astronomers find a few nearby novae (plural of *nova*) each year, but supernovae (plural) are so rare that only one or two happen each century in our galaxy. In the previous chapter, you saw that stars resist their own gravity by generating energy through nuclear fusion. The energy keeps their interiors hot, and the resulting high pressure balances gravity and prevents the star from collapsing. Stars, however, have limited fuel. When they exhaust their fuel, gravity wins, and the stars die.

The mass of a star is critical in determining its fate. Massive stars use up their nuclear fuel at a furious rate and die after only a few million years. In contrast, the lowest-mass stars use their fuel sparingly and may be able to live hundreds of billions of years (refer to Table 7.2). Stars with different masses lead dramatically different lives and die in different ways.

nova From the Latin, meaning "new," a sudden and temporary brightening of a star, making it appear as a new star in the sky; evidently caused by an explosion of nuclear fuel on the surface of a white dwarf.

supernova A "new star" in the sky that is up to 50 000 times more luminous than a normal nova and longer lasting; evidently the result of an explosion of a star.

8.1 The Beginning of the End

The life cycle of a star consists of many stages. The number, sequence, and timing of these stages depends sensitively on the mass of the star. For the purposes of understanding how they die, we can group stars into two categories: low-mass stars, which have masses below around 8 solar masses, and high-mass stars, which have masses of 8 solar masses and higher. All stars begin to die for the same reasons and proceed through some of the same stages. Low-mass stars trudge slowly through some of the stages, then die quietly. High-mass stars race through many more stages then die violently. We'll explore the deaths of low-mass stars first, then discuss how high-mass star death differs.

Red Dwarf Stars

Main-sequence stars generate their energy by nuclear fusion reactions that combine hydrogen to make helium. The more massive a star, the more quickly it consumes its hydrogen fuel. The very least massive stars are red dwarfs, with masses between about 0.08 and 0.5 solar masses. The low masses of these stars mean that they produce less gravity than other stars, so they don't need to produce as much energy and pressure to resist gravity's inward pull. So, red dwarf stars use their hydrogen fuel slowly. These stars also have strongly convective interiors. This means that, as they produce helium in their cores, rising currents carry the hot helium away and replenish the core with new hydrogen from the star's outer layers. With their slow fusion rates and their fuel recycling, red dwarfs can continue to fuse hydrogen for hundreds of billions, even *trillions* of years before they run out. These are the most common types of stars in the universe, and none of them has yet had the chance to run out of fuel. Every red dwarf ever formed is still alive today!

Sunlike Stars

Stars like the Sun, with masses around 1 solar mass, aren't so fortunate. The Sun lacks the deep convective layer of a red dwarf. Although it has more hydrogen fuel overall, it consumes it more quickly and can't replenish it from its outer layers. A sunlike star fuses hydrogen in its core for about 90 percent its total lifetime, which is about 10 billion years. When its core hydrogen is exhausted, however, it begins to evolve rapidly, changing its structure, energy source, and appearance. What prompts this change?

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Expansion into a Giant

The nuclear reactions in a main-sequence star's core produce helium. The cores of main-sequence stars do not get hot enough to fuse helium to form heavier elements, so helium accumulates at their centres like ashes in a fireplace. Initially, this helium ash has little effect on a star, but as hydrogen is exhausted and the stellar core becomes almost pure helium, the star's ability to generate nuclear energy is reduced. Because the energy generated at the centre is what opposes gravity and supports the star, the core begins to contract as soon as the energy generation starts to decline.

Although the core of helium ash cannot generate nuclear energy, it can grow hotter because it contracts and converts gravitational energy into thermal energy. In Chapter 7, we discussed how this same mechanism is responsible for heating up collapsing clouds of gas and dust as they turn into stars. In a dying star, the rising temperature heats the unprocessed hydrogen just outside the core—hydrogen that was never previously hot enough to fuse. When the temperature of the surrounding hydrogen becomes high enough, hydrogen fusion begins in a spherical layer, called a shell, surrounding the exhausted core of the star. Like a grass fire burning outward from an exhausted campfire, the hydrogen-fusion shell creeps outward, leaving helium ash behind and increasing the mass of the helium core.

This hydrogen-fusion shell produces energy at a tremendous rate—even higher than the hydrogen-fusion core did. Figure 8.1 illustrates how the flood of energy produced by the hydrogen-fusion shell pushes toward the surface, forcing the outer layers of the star to expand dramatically. Stars like the Sun become **giant stars** 10 to 100 times the present diameter of the Sun. When the Sun dies, its outermost layers will be so cool that it will become a **red giant**. As we shall see, the same process also occurs in very massive stars, turning them into **supergiant stars**, as much as 1000 times larger than the Sun.

The expansion of a star to giant or supergiant size cools the star's outer layers. The star becomes larger and redder, moving toward the upper right in the H–R diagram. Look back at Figure 6.8 and notice that some of the most familiar stars, such as Aldebaran, Betelgeuse, and Polaris, are giants or supergiants.

Although the energy output of the hydrogen-fusion shell can force the envelope of the star to expand, it cannot stop the contraction of the helium core. Because the core is not hot enough to fuse helium and produce pressure to counteract gravity, it gets squeezed to a relatively tiny size. If you represented a typical giant star as the size of a baseball stadium, its helium core would be only about the size of a baseball, yet it would contain about 10 percent of the star's mass.

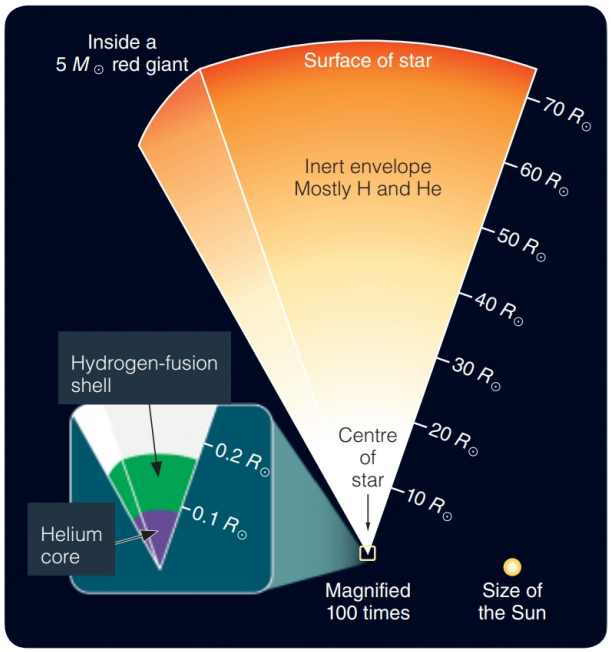


Figure 8.1 When a star runs out of hydrogen at its centre, the core contracts to a small size and becomes very hot, igniting hydrogen fusion in a shell around it (green). The outer layers of the star expand and cool. The red giant star shown here has an average density much lower than the air at Earth's surface. Here $M_\odot$ stands for the mass of the Sun, and $R_\odot$ stands for the radius of the Sun.

Helium Fusion

As a star becomes a giant, fusing hydrogen in a shell, the inert core of helium ash contracts and grows hotter. When the core finally reaches a temperature of 100 000 000 K, helium nuclei can begin fusing to make carbon nuclei. Red dwarf stars never reach this state, but other low-mass stars and all high-mass stars do.

The ignition of helium in the core changes the structure of the star. The star now makes energy in two locations by two different processes: helium fusion in the core and hydrogen

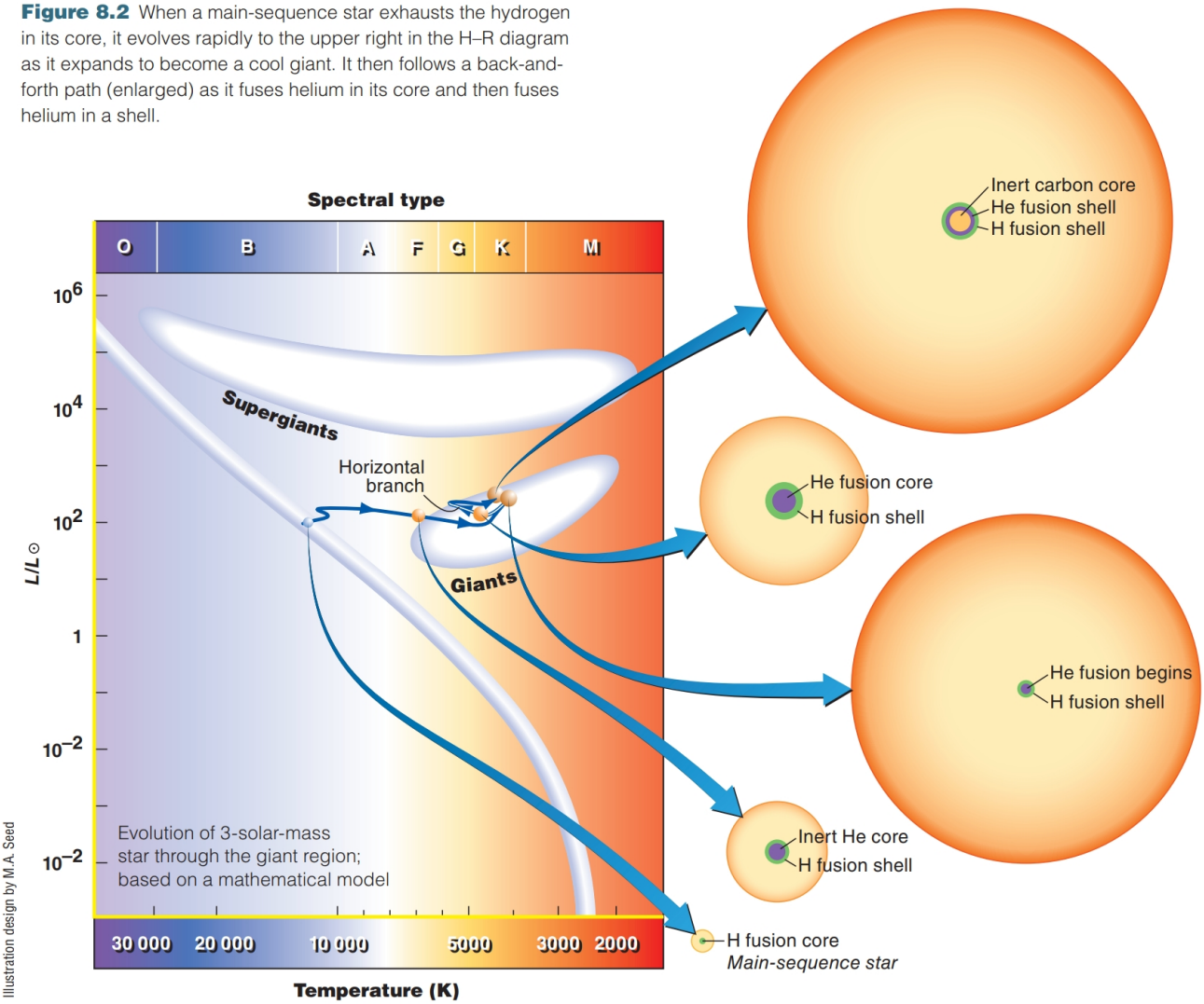
giant star Large, cool, highly luminous star in the upper right corner of the H–R diagram, typically 10 to 100 times the diameter of the Sun.

red giant A very large, very luminous star in the late stages of its evolution. Intense fusion in shells causes the outer layers to puff up, cool down, and appear red.

supergiant star Exceptionally luminous star whose diameter is 100 to 1000 times that of the Sun.

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Figure 8.2 When a main-sequence star exhausts the hydrogen in its core, it evolves rapidly to the upper right in the H–R diagram as it expands to become a cool giant. It then follows a back-and-forth path (enlarged) as it fuses helium in its core and then fuses helium in a shell.



fusion in the surrounding shell. The energy flowing outward from the core halts the contraction of the core, and at the same time the star's envelope contracts and grows hotter. Consequently, the point that represents the star in the H–R diagram moves downward—corresponding to lower luminosities—and to the left—corresponding to higher surface temperatures—to a region above the main sequence called the **horizontal branch**. (See Figure 8.2 and **Visualizing Astronomy 8.1, Star Cluster H–R Diagrams**.) Astronomers sometimes refer to stars with those characteristics as "yellow giants."

horizontal branch The location in the H–R diagram of giant stars that are fusing helium in their cores.

Helium fusion produces carbon and oxygen that again accumulate in an inert core. Recall that the end of core hydrogen fusion caused the core to contract and heat up, igniting a hydrogen-fusion shell around the inert helium core. Similarly, the end of core helium fusion causes the core to contract and heat up, igniting a helium-fusion shell around the inert carbon–oxygen core. The helium-fusion shell is surrounded by a hydrogen-fusion shell. These two shells produce a flood of energy, so the star quickly expands, and its surface cools once again. The point that represents the star in the H–R diagram moves back to the right, and the star becomes a red giant again. The approximate rule is that if the core of a post–main-sequence star is "dead" (has no nuclear reactions), the star is a red giant, and if the core is "alive" (has fusion reactions), the star is a yellow giant.

Now you can understand why giant stars are relatively rare (refer to **Visualizing Astronomy 6.1, The Family of Stars**). A star spends about 90 percent of its

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lifetime on the main sequence and only 10 percent as a giant star. At any moment you look, only a fraction of the visible stars will be passing through the red and yellow giant stages.

What happens to a star after helium fusion depends on its mass, but in any event it cannot survive for long. It must eventually collapse and end its career as a star. The remainder of this chapter will trace the details of this process of stellar death, but before you begin that story, you must ask the most important question in science: What is the evidence? What evidence shows that stars actually evolve as theory predicts? You can find the answers in observations of star clusters.

Star Clusters: Evidence of Evolution

In scientific experiments, it is important to control variables. Imagine you want to test the effect of temperature on the cleaning power of a certain laundry detergent. To isolate the effect of temperature, you must ensure everything else is the same: the same fabrics washed in the same machines with the same amount of detergent. Only the temperature should vary from one experiment to the next. Astronomers can't usually control variables in this way. They can try to compare similar stars, but even similar-seeming stars may differ in their ages, chemical compositions, or masses, making it difficult to determine the effects of each of those variables. Fortunately, nature has provided a solution to this problem: star clusters.

The stars in a star cluster all formed at about the same time and from the same cloud of gas, so they must be about the same age and chemical composition. The main thing that differs among stars in a cluster is their masses. So, by observing star clusters, astronomers can determine the effect of mass on stellar evolution.

Study **Visualizing Astronomy 8.1, Star Cluster H–R Diagrams**, and notice three important points:

1. There are two kinds of star clusters, but they are similar in the way their stars evolve. You will learn more about these clusters in the next chapter.
2. You can estimate the age of a star cluster by observing the distribution of the points that represent its stars in the H–R diagram.
3. Finally, a star cluster's H–R diagram shape is governed by the evolutionary path the stars take. By comparing clusters of different ages, you can visualize how stars evolve almost as if you were watching a film of a single star cluster changing over billions of years.

Were it not for star clusters, astronomers would have little confidence in the theories of stellar evolution. Star clusters make that evolution visible and assure astronomers that they really do understand how stars are born, live, and die.

8.2 The Final End of a Low-Mass Star

For a low-mass star, the formation of a carbon–oxygen core is fatal. These stars will never achieve the temperatures needed to fuse either carbon or oxygen. Instead, the core of the star becomes inert and fusion transfers to shells fusing helium and hydrogen. As we have discussed, the tremendous energy produced by these shells causes the outer layers to expand and cool, turning the star into a red giant. During the red giant stages, stars tend to lose mass due to strong stellar winds. When a star becomes a red giant, its atmosphere becomes cool and consequently more opaque. The more opaque these layers become, the greater the push they feel from light escaping from the interior of the star. At the same time, the fusion shells become thin, which causes them to burn unstably. They begin to release their energy in bursts, which push the atmosphere outward. An aging giant can expel its outer atmosphere in repeated surges.

Planetary Nebulae

What evidence is there that these unseen processes, occurring deep within stars, actually take place? As it happens, the sky is littered with the remains of dead low-mass stars in the form of **planetary nebulae**, such as those shown in Figure 8.3. These highly photogenic clouds of ionized gases are the result of the surges that push the outer layers of a dying sunlike star out into space. Their name is a misnomer: the astronomers who made the first discoveries of planetary nebulae using small telescopes mistook them for the greenish-blue disks of planets such as Uranus or Neptune. In fact, planetary nebulae have nothing to do with planets.

You can understand what planetary nebulae are like by using simple observations and theoretical methods explained in Chapter 5, such as Kirchhoff's laws and the Doppler effect. Although real

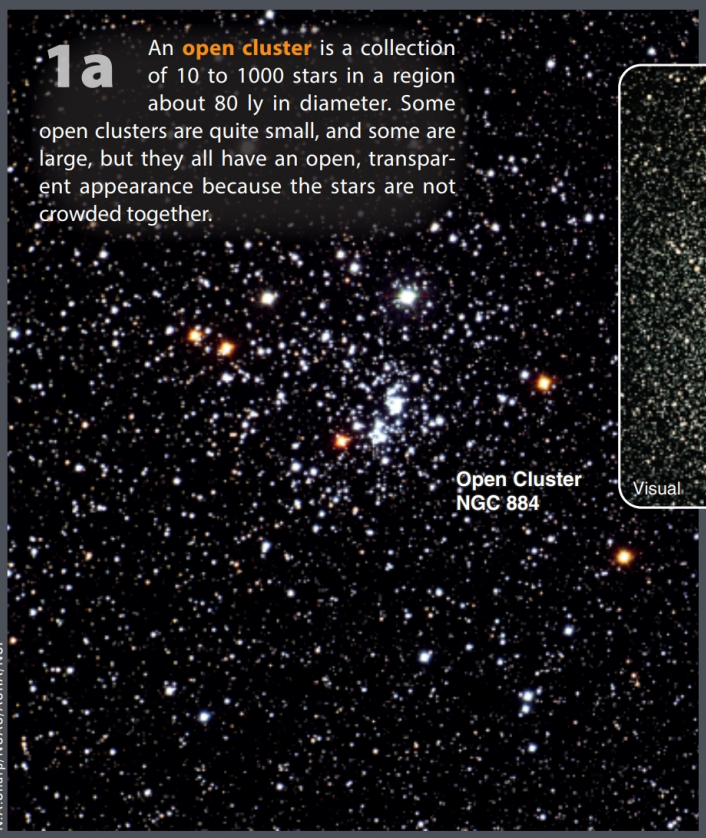
planetary nebula An expanding shell of gas ejected from a medium-mass star during the latter stages of its evolution.

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Visualizing Astronomy 8.1

1 STAR CLUSTER H–R DIAGRAMS

1a An **open cluster** is a collection of 10 to 1000 stars in a region about 80 ly in diameter. Some open clusters are quite small, and some are large, but they all have an open, transparent appearance because the stars are not crowded together.



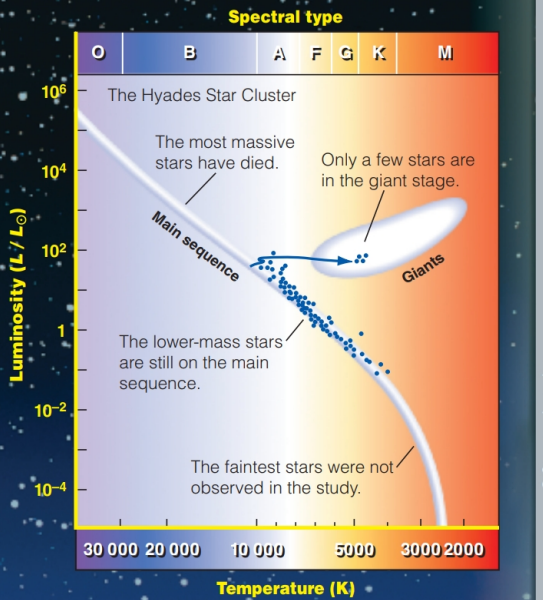
N.A.Sharp/NOAO/AURA/NSF



Anglo-Australian Observatory / David Malin Images

1b A **globular cluster** can contain 10^5 to 10^6 stars in a region only 30 ly to 100 ly in diameter. The term *globular cluster* comes from the word *globe*, although globular cluster is pronounced like glob as in *glob* of butter. These clusters are nearly spherical, and the stars are much closer together than the stars in an open cluster.

Astronomers can construct an H–R diagram for a star cluster by plotting a point to represent the luminosity and temperature of each star.



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2 The H–R diagram of a star cluster can make the evolution of stars visible. The key is to remember that all of the stars in the star cluster have the same age and composition, differing only in mass. The H–R diagram of a star cluster provides a "snapshot" of the evolutionary state of the stars at the time you happen to observe them. This diagram shows the 650-million-year-old star cluster called the Hyades, easily visible to the unaided eye in the constellation Taurus. The upper main sequence is missing because the more massive stars have died, and this snapshot catches a few medium-mass stars leaving the main sequence to become giants.

As a star cluster ages, its main sequence grows shorter, like a candle burning down. You can judge the age of a star cluster by looking at the turnoff point, the point on the main sequence where stars are currently evolving to the right to become giants. Stars at the **turnoff point** have lived out their lives and are about to die. Consequently, the life expectancy of the stars at the turnoff point equals the age of the cluster. (Evolutionary track adapted from the work of Icko Iben.)

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3 From theoretical models of stars, you could construct a film to show how the H–R diagram of a star cluster changes as it ages. You can then compare theory (*left*) with observation (*right*) to understand how stars evolve. Note that the time step for each frame in this film increases by a factor of 10.

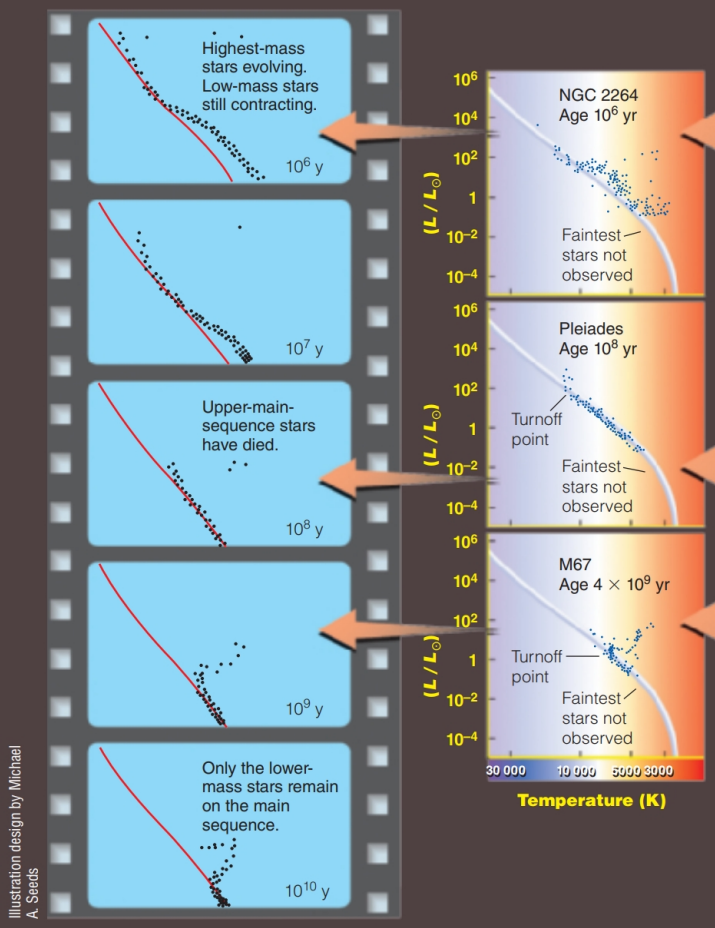
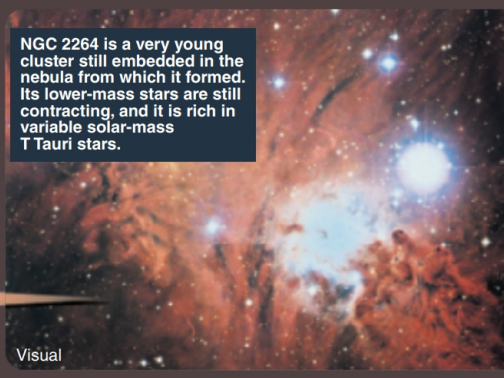
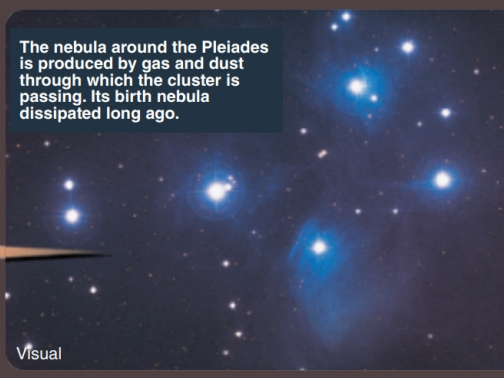


Illustration design by Michael A. Seeds



Anglo-Australian Observatory / David Malin Images

NGC 2264 is a very young cluster still embedded in the nebula from which it formed. Its lower-mass stars are still contracting, and it is rich in variable solar-mass T Tauri stars.



Caltech

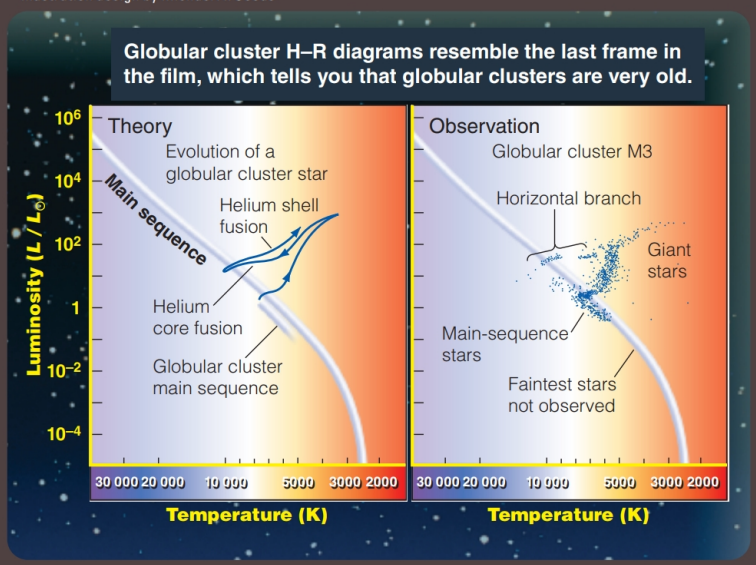
The nebula around the Pleiades is produced by gas and dust through which the cluster is passing. Its birth nebula dissipated long ago.



Nigel Sharp, Mark Hanna/NOAO/AURA/NSF

M67 is an old open cluster. In photographs, such clusters have a uniform appearance because they lack hot, bright stars. Contrast with the NGC 884 cluster on the opposite page.

Illustration design by Michael A. Seeds

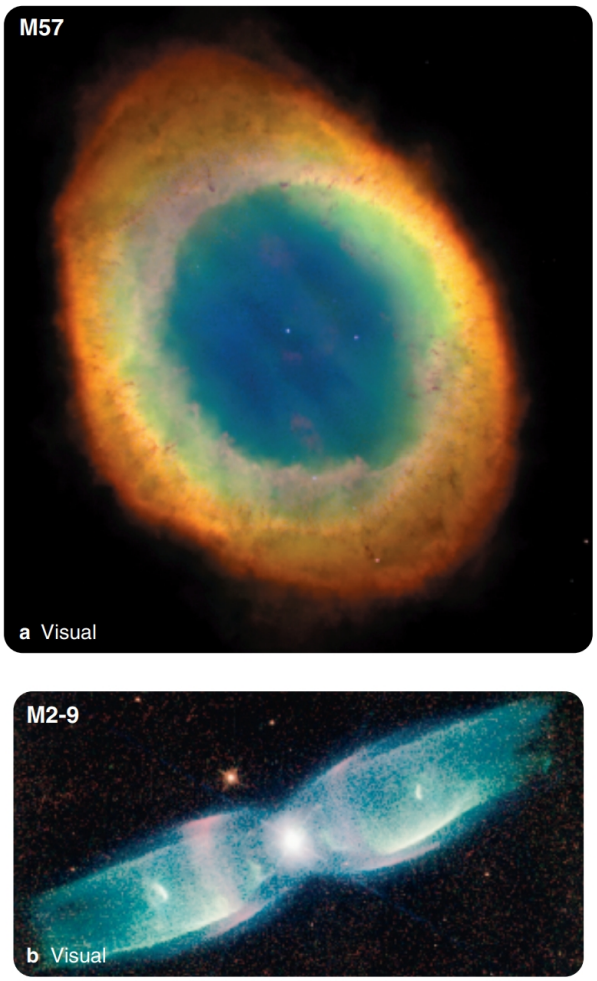


3a The H–R diagrams of globular clusters have very faint (low-luminosity, low-mass) turnoff points showing that they are very old clusters. The most complete analysis suggests these clusters are about 11 billion years old.

The **horizontal branch** stars are giants fusing helium in their cores or in shells. The shape of the horizontal branch outlines the evolution of these stars.

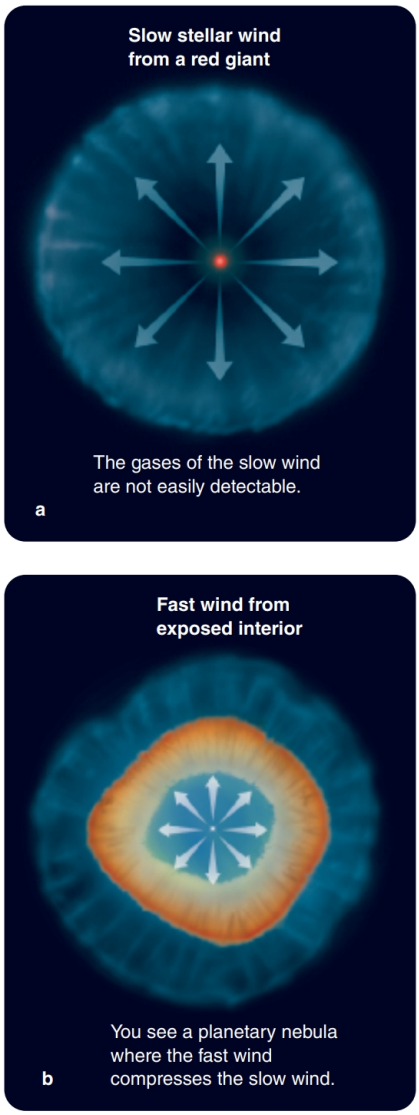
The main-sequence stars in globular clusters are fainter and bluer than the zero-age main sequence. Spectra reveal that globular cluster stars are poor in elements heavier than helium, which means their gases are less opaque. That means energy can flow outward more easily, making these low-metallicity stars slightly smaller and hotter than their high-metallicity counterparts with the same masses.

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Hubble Heritage Team, STScI/AURA/NASA, NASA

Figure 8.3 (a) The Ring Nebula in the constellation Lyra is visible even in small telescopes. Note the hot blue star at its centre and the radial texture in the gas that suggests outward motion. (b) Some planetary nebulae such as M2-9 are highly elongated, and it has been suggested that the Ring Nebula in (a) actually has a tubular shape, like M2-9, that happens to be pointed approximately toward Earth.



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Figure 8.4 The process that produces planetary nebulae involves two stellar winds. First, as an aging giant, the star gradually blows away its outer layers in a slow breeze of relatively cool gas that is not easily visible. Once the hot interior of the star is exposed, it ejects a high-speed wind that overtakes and compresses the gas of the slow wind—like a snowplow. The ultraviolet radiation from the hot remains of the central star excites the gases to glow like a giant neon sign.

nebulae are quite complex, the simple model shown in Figure 8.4 of a slow stellar wind followed by a fast wind explains their structures fairly well and provides a way to organize the observed phenomena. The complexities and asymmetries seen in planetary nebulae may be due to repeated expulsions of expanding shells and oppositely directed jets, much like the bipolar flows observed coming from protostars.

White Dwarfs

We have learned that the outer layers of a dying low-mass star become a planetary nebula, but what happens to the leftover cores of these stars? In short, very little. Once the core of a low-mass star ceases fusion reactions, it no longer produces enough energy to support itself against its own gravity. The resulting compression squeezes it to a tiny fraction of its former size. It is still extremely hot, so it glows white. These objects are known as white dwarfs.

The first white dwarf discovered was the faint companion to the well-known star Sirius, the brightest star in the sky. Sirius is a visual binary star, the most luminous

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member of which is Sirius A. The white dwarf, Sirius B, is 10 000 times fainter than Sirius A. The orbital motions of the stars (Figure 6.12) reveal that the white dwarf's mass is 0.98 solar mass, and its blue-white colour tells you that its surface is hot, about 25 000 K. Although it is very hot, it has a very low luminosity, so it must have a small surface area. In fact, it is about the size of Earth. Dividing its mass by its volume reveals that it is very dense, about 2 million grams per cubic centimetre. On Earth, a teaspoonful of Sirius B material would weigh more than 11 tons. These basic observations and simple physics lead to the conclusion that white dwarfs are astonishingly dense.

How can an object as dense as a white dwarf support itself against the crush of its own gravity if it can't produce energy through nuclear fusion? Electrons normally repel one another because of their similar electric charges. When they are packed very closely together, an additional quantum mechanical effect called degeneracy pressure kicks in and halts the collapse of the star. Matter in this state is known as **degenerate matter**, and it has two unusual properties. Degenerate matter is millions of times harder to compress than solid steel, and its pressure no longer depends on its temperature. Unlike a main-sequence star, which is supported by ordinary gas pressure, a white dwarf is supported against its own gravity by degeneracy pressure.

Clearly, a white dwarf is not a true star. It generates no energy by nuclear reactions, is almost completely degenerate matter, and, except for a thin layer at its surface, contains no gas. Instead of calling a white dwarf a "star," you could call it a **compact object**. Later sections of this chapter discuss two other types of compact objects: neutron stars and black holes.

A white dwarf's future is bleak. As it radiates energy into space, its temperature gradually falls, but it cannot shrink any smaller because its degenerate electrons cannot get closer together. Instead, an aging white dwarf gets fainter and cooler, moving downward and to the right in the H–R diagram, much like the slowly cooling embers that remain after a fire has gone out. Because a white dwarf contains a tremendous amount of heat, it needs billions of years to radiate that heat through its small surface area. The coolest white dwarfs in our galaxy have about the same surface temperature as the Sun.

Mathematical models tell us that there is an upper limit to the masses of white dwarfs. Electron degeneracy pressure cannot support an object with a mass greater than about 1.4 solar masses. This is called the **Chandrasekhar limit**, after Indian astrophysicist Subrahmanyan Chandrasekhar, whose work on this and other problems earned him the 1983 Nobel Prize in Physics. This limit seems to imply that a star more massive than 1.4 solar masses could not become a white dwarf unless it got rid of the extra mass in some way. As we have seen, stars evolving through the giant stage can lose significant fractions of their mass, in the form of stellar winds and the ejection of planetary nebulae. Models predict that stars that begin their main-sequence lives with masses up to about 8 solar masses can eventually lose enough mass to end up as white dwarfs.

The Fate of the Sun and the End of Earth

What will happen to our Earth and all the life on it when the Sun dies? Stellar evolution models predict that, over the course of the next few billion years, the Sun will gradually brighten as it exhausts its hydrogen fuel. Eventually, the rising luminosity of the Sun will trigger a runaway greenhouse effect that will render Earth uninhabitable.

Evolutionary models of the Sun suggest that it is about halfway through its main-sequence lifetime. In about 5 billion years, it will exhaust the hydrogen in its core, begin burning hydrogen in a shell, and swell into a red giant star about 30 times its present radius. Later, helium fusion will ignite in the core, and the Sun will become a horizontal branch star. Once the helium fuel is exhausted in its core, helium fusion will begin in a shell, and the Sun will expand again. That second red giant version of the Sun will be about as large as the orbit of Earth (see Figure 8.5). Astronomers are still uncertain about some of the details, but computer models that include tidal effects predict that the expanding Sun eventually will engulf and destroy Mercury, Venus, and Earth.

While it is a giant star, the Sun will have a strong wind and lose a substantial fraction of its mass into space. The remainder will collapse to become a white dwarf. Astronomers can't yet predict whether the white dwarf will be hot enough to ionize the expelled gases and light them up as a planetary nebula. We *can* say with reasonable confidence that the atoms that make up the biosphere on Earth—including you—will be vaporized and ejected into space, where some of them may

degenerate matter Extremely high-density matter in which pressure no longer depends on temperature due to quantum mechanical effects.

compact object One of the three final states of stellar evolution, which generates no nuclear energy and is much smaller and denser than a normal star.

Chandrasekhar limit The maximum mass of a white dwarf, about 1.4 solar masses. A white dwarf of greater mass cannot support itself and will collapse.

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Figure 8.5 Relative sizes of the Sun now, the Sun as a red giant, and Earth as a reference for the Sun as an Earth-sized white dwarf at the end of its life.

Roche lobe The teardrop-shaped volume of space a star controls gravitationally within a binary system.

angular momentum A measure of the tendency of a rotating body to continue rotating.

accretion disk The rotating disk that forms in some situations as matter is drawn gravitationally toward a central body.

rejoin the interstellar medium and eventually become part of new generations of stars.

Although this expansion of the Sun and the expulsion of its outer layers sounds like a violent process, it is actually a very slow one, taking hundreds of millions of years. It's not an explosion. As we shall soon see, only very massive stars die in violent explosions.

8.3 The Evolution of Binary Systems

So far, we have mainly considered the evolution of single stars. However, recall that most stars in the universe occur in binary systems and other multiples. If the spacing of the stars in a binary system is large enough, they can evolve and die almost as if they were independent stars. However, when binary stars orbit very close to one another, the death of one can have surprising effects on the other.

Mass Transfer and Accretion Disks

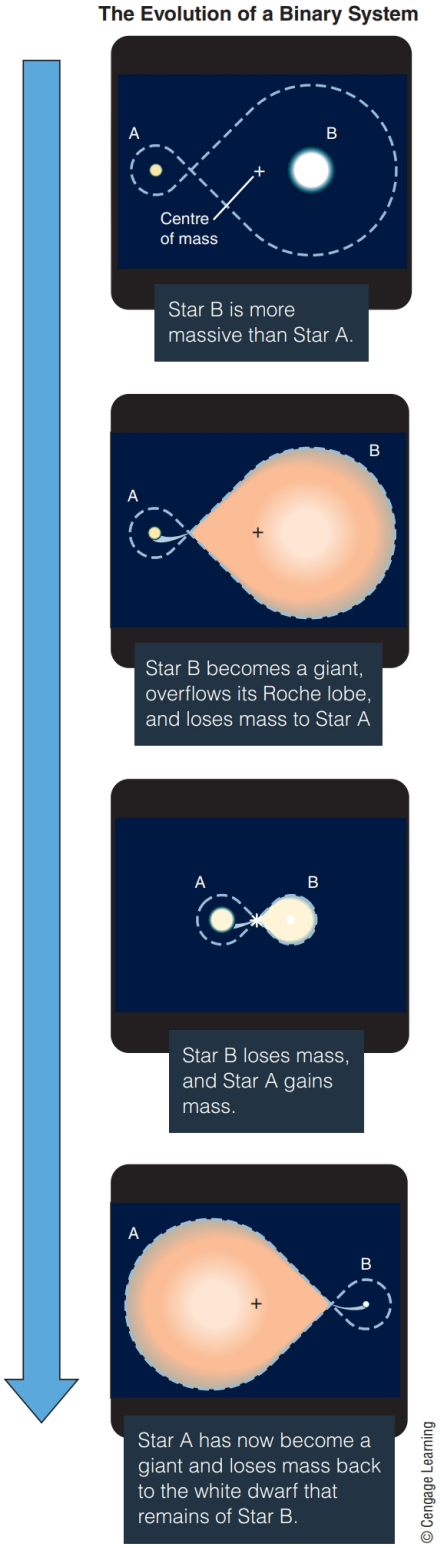
When two stars are close to one another, the gravity of each one pulls on the outer layers of the other. There is a balance point somewhere between them at which material is equally attracted to both stars. Any material passing this balance point will flow from one star to the other. In fact, after taking into account the rotation of the system, we find that the gravity of each star dominates in a teardrop-shaped region called a **Roche lobe**. Matter inside a star's Roche lobe is gravitationally bound to that star, but matter that leaves the lobe can be transferred to the other star or lost completely from the system. When an evolving star in a close binary system expands so far that it fills its Roche lobe, matter from that star may overflow the lobe and be transferred to the other star, as you can see in the series in Figure 8.6.

Matter flowing from one star to another cannot fall directly into the star. Rather, because of conservation of angular momentum, it must flow into a whirling disk around the star. **Angular momentum** refers to the tendency of a rotating object to continue rotating. Mathematically, it's the product of the object's mass, velocity, and radius. All rotating objects possess some angular momentum, and in the absence of external forces, that angular momentum remains unchanged (conserved). A figure skater takes advantage of conservation of angular momentum by starting a spin slowly with arms extended and then drawing them in. This brings more of her mass to smaller radii, which must be compensated for by a higher rate of rotation if her total angular momentum is to remain unchanged. So, as she contracts, she spins faster.

Mass transferred from one star to another in a binary star system must conserve its angular momentum. Thus, it must flow into a rapidly rotating whirlpool called an **accretion disk** around the second star. The gas in the disk grows hot due to friction and tidal forces (see Chapter 2)

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Figure 8.6 A pair of stars orbiting close to each other can exchange mass and modify their evolution. Here, the dotted white lines indicate the Roche lobes of each star.



and eventually falls onto the second star. If that second star is a compact object such as a white dwarf, the gas in the accretion disk can become very compressed. The gas temperature can exceed a million K, producing X-rays and a flare-up in visible light called a nova.

Novae

At the beginning of this chapter you saw that the word *nova* refers to an apparently new star that appears in the sky for a while and then fades away. Modern astronomers know that a nova is not a new star but an old star flaring up. After a nova fades, astronomers can photograph the spectrum of the remaining faint point of light. Invariably, they find a normal star and a white dwarf in a close binary system. A nova is evidently an explosion involving a white dwarf.

Observational evidence can tell you how nova explosions occur. When the explosion begins, spectra show blueshifted absorption lines that become blueshifted emission lines after a few days. The blueshift tells us that the material is rushing toward us (away from the source), while the shift from absorption to emission lines tell us that the material has thinned out as it expands and is allowing light to pass freely through it.

Nova explosions occur when mass transfers from a main-sequence or giant star into an accretion disk around a white dwarf (Figure 8.7). As the matter loses its angular momentum in the accretion disk, it settles inward onto the surface of the white dwarf and forms a layer

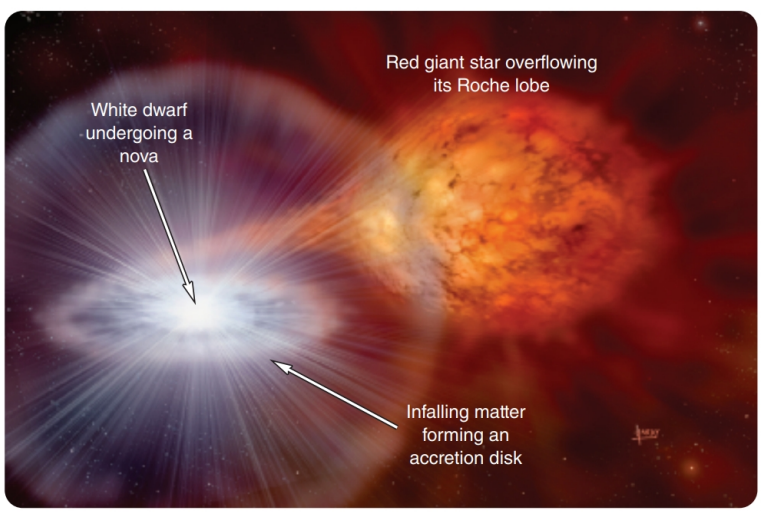
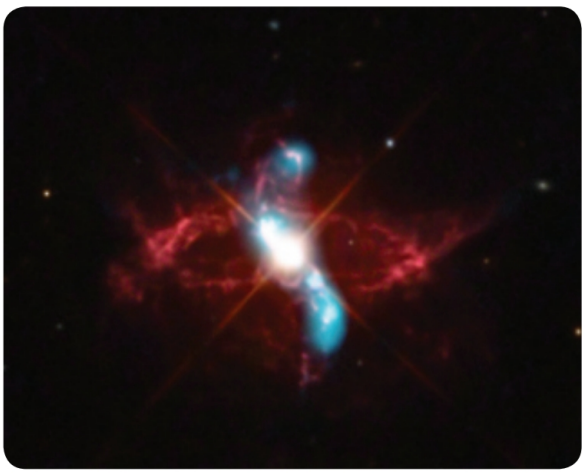


Figure 8.7 Matter from an evolving red giant falls into a white dwarf and forms a whirling accretion disk. Friction and tidal forces can make the disk very hot. Such systems can lead to nova explosions on the surface of the white dwarf as shown in this artist's impression.

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X-ray: NASA/CXC/SAO/R. Montez et al.; Optical: Adam Block/Mt. Lemmon SkyCenter/U. Arizona

Figure 8.8 A ring of material ejected during a nova eruption in the binary star system R Aquarii. The red ring of material is gas expelled by the nova, seen in visible light. Blue colours represent X-rays thought to be the product of shock waves created when the gas expelled by the nova runs into surrounding material.

of unused nuclear fuel—mostly hydrogen. As the layer deepens, it becomes denser and hotter until the hydrogen fuses in a sudden explosion that blows the surface off the white dwarf (Figure 8.8). Although the expanding cloud of debris contains less than 0.0001 solar mass, it is hot, and its expanding surface area makes it very luminous. Nova explosions can become 100 000 times more luminous than the Sun. As the debris cloud expands, cools, and thins over a period of weeks and months, the nova fades from view.

The explosion of its surface hardly disturbs the white dwarf and its companion star. Mass transfer quickly resumes, and a new layer of fuel begins to accumulate. This is why some binary star systems undergo similar novae many times.

Type Ia Supernova: Thermonuclear or White Dwarf Supernova

When a white dwarf in a binary system accretes enough material to approach or exceed the Chandrasekhar limit, the result is not a nova, but a supernova. A nova is the explosive ignition of some accreted material on the surface of the white dwarf, whereas a supernova is the explosion of the entire white dwarf itself. For reasons we will come to, the explosion of an accreting white dwarf is called a type Ia supernova.

The exact detonation mechanism of type Ia supernovae is still disputed. However, the most widely accepted model says that the accretion of new material onto a white dwarf compresses the core enough to ignite carbon fusion. A wave of carbon fusion passes through the white dwarf, releasing tremendous amounts of energy very quickly and tearing the star apart in mere seconds. A single white dwarf supernova can shine with a luminosity four billion times that of the Sun, before fading away over a few weeks.

All type Ia supernovae appear to explode with close to the same maximum luminosity, which makes sense if they are all explosions of very similar objects. This makes them extremely useful tools for measuring astronomical distances. Because we know their luminosities are all the same, we can measure the apparent brightness of any given type Ia supernova and then use the inverse square law to calculate its distance. This useful property of type Ia supernovae explains why they are known as "standard candles." In Chapters 10 and 11, you'll learn more about why supernova standard candles are essential to our understanding of the universe.

8.4 The Deaths of Massive Stars

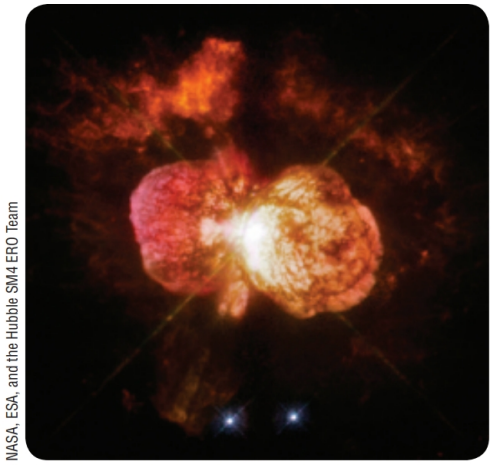
You have seen that low-mass stars die relatively quietly as they exhaust their core hydrogen and helium, push away their surface layers, and form planetary nebulae. By contrast, massive stars destroy themselves in violent explosions (see Figure 8.9).

Nuclear Fusion in Massive Stars

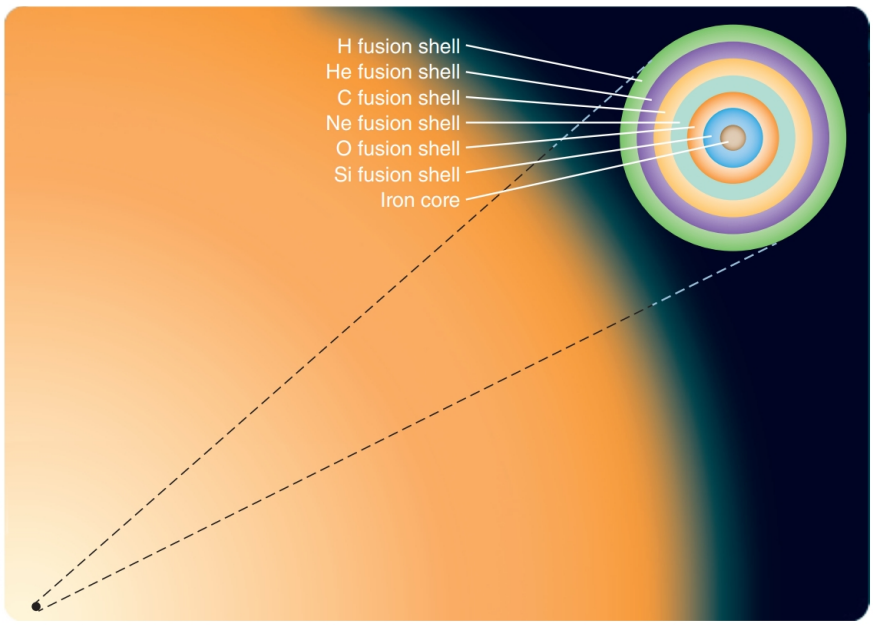
Massive stars die for the same reason as low-mass stars: they run out of nuclear fuel in their cores. Like low-mass stars, massive stars exhaust their core hydrogen, ignite hydrogen shells, and become giants or supergiants. Their cores contract and fuse helium first in the core and then in a shell, producing a carbon–oxygen core.

From that point on, the evolution of stars above about 8 to 10 solar masses is very different from those of lower masses. In these stars, the contraction of the carbon core eventually produces temperatures around 1 billion Kelvin, igniting carbon fusion. Carbon fusion produces oxygen and neon. When carbon is exhausted in the core, the core contracts and carbon fusion transfers to a shell. This pattern of core ignition and shell ignition continues with a series of heavier nuclei as fusion fuel, and the star develops a layered structure with a hydrogen-fusion shell surrounding a helium-fusion shell surrounding a

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Figure 8.9 Schematic diagram of the structure of a very massive star shortly before its death in a supernova explosion. The core of the star has separated into layers, with each layer fusing a slightly heavier element than the one farther out. The inset shows the star Eta Carinae, a star with a mass of more than 100 solar masses. Eta Carinae has undergone many violent outbursts in the last few centuries, evidenced by the clouds of material blown off its surface and visible in this image.

carbon-fusion shell and so on (Figure 8.9). At higher temperatures than carbon fusion, nuclei of oxygen, neon, and magnesium fuse to make silicon and sulphur, and at even higher temperatures silicon can fuse to make iron.

The fusion of the nuclear fuels in this series goes faster and faster as the massive star evolves rapidly. The amount of energy released per fusion reaction decreases as the mass of the types of atoms involved increases. To support its weight and remain stable, a star must fuse oxygen much faster than it fused hydrogen, because each oxygen fusion reaction releases less energy than a hydrogen fusion reaction. Also, there are fewer nuclei in the core of the star by the time heavy nuclei begin to fuse. Four hydrogen nuclei make one helium nucleus, and three helium nuclei make one carbon; so, there are 12 times fewer nuclei of carbon available for fusion than there were hydrogen nuclei. This means the heavy elements are used up more quickly, and fusion goes very quickly in massive stars (Table 8.1). Hydrogen fusion can last 5 million years in a 40-solar-mass star, but that same star fuses its oxygen in two months and its silicon in less than a day.

Supernova Explosions of Massive Stars

When a massive star develops a silicon core, it is almost at the end of its lifetime. Silicon fuses to produce iron. You might imagine that, because there are many elements in the periodic table heavier than iron, fusion continues until all of these elements are produced. This is not the case. The production of an iron core heralds the violent death of the star. Why can't stars fuse iron to produce heavier elements? Technically, it is possible to produce heavy elements by fusion, but it can't happen in a sustainable way in stars. As we learned in Chapter 7, the protons and neutrons in an iron nucleus are so tightly bound that no energy can be extracted by fusing iron nuclei. Instead, fusing two iron nuclei would result in a nucleus that is *less* tightly bound than the original iron nuclei. This process would *consume* energy, so it can't power a star. To return to our hydroelectric dam analogy from Chapter 7, trying to power a star by fusing iron nuclei would be like trying to run a hydroelectric dam by hauling water from the bottom back to the top.

Table 8.1 Heavy-Element Fusion in a 40-Solar-Mass Star

Fuel	Time	Percentage of Lifetime
H	5 000 000 years	93
He	400 000 years	7.3
C	190 years	0.004
O	58 days	0.000003
Si	0.5 days	0.00000003

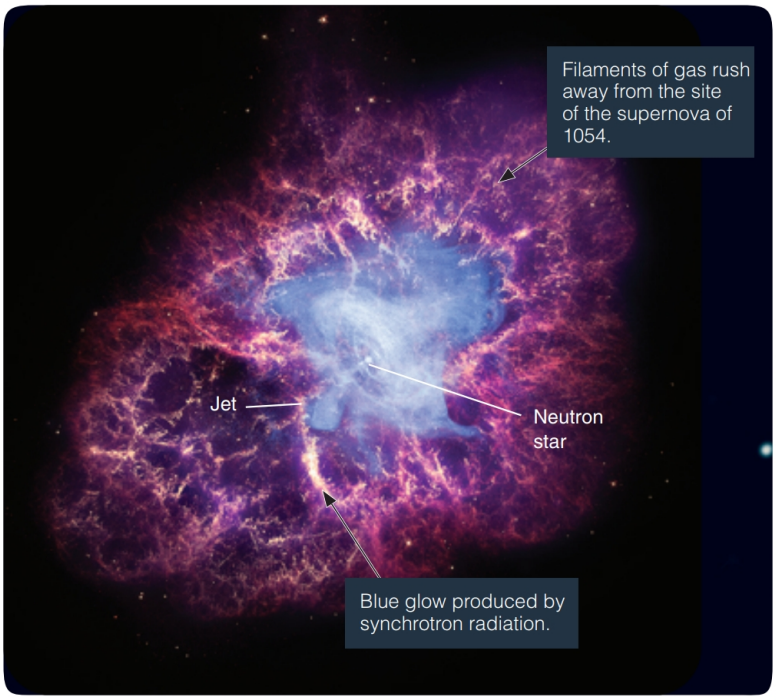
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So, once a star develops an iron core, it can no longer produce the energy needed to create the pressure that supports it against its own gravity. The star is doomed.

Once core fusion shuts off in a massive star, gravity takes over and crushes it. You might think that electron degeneracy pressure would rescue the star from total collapse, forming a white dwarf. Not so! The tremendous forces inside a massive star actually cause the electrons to combine with the protons, forming neutrons and releasing a flood of neutrinos (see Chapter 7). The elimination of the electrons means that electron degeneracy pressure can't halt the collapse of the core, which is why high-mass stars don't end up as white dwarfs.

For a short time the core produces more energy per second than all the stars in all of the visible galaxies in the universe, and 99 percent of that energy is in the form of neutrinos. This flood of neutrinos carries large amounts of energy out of the core, allowing the core to collapse further. This process happens rapidly, taking less than a second. Computer models of the collapse of the core struggle to keep up with the details of so many events happening so quickly. What we can say with reasonable confidence is that, as the core collapses, eventually the neutrons are squeezed together so tightly that neutron degeneracy pressure becomes a dominant force. Neutron degeneracy pressure is similar to electron degeneracy pressure: both are quantum mechanical effects that make further compression impossible. The sudden onset of neutron degeneracy pressure creates an "immovable wall" against which the rest of the infalling material rebounds in a colossal shock wave. The rebounding material is further propelled by the burst of neutrinos, driving most of the star's mass away from the core in a supernova explosion.

What's left of the star depends on its initial mass and its chemical composition. For stars less than about 20 solar masses, the degenerate core of neutrons can survive as a neutron star. For stars up to about 50 solar masses, the neutrons themselves may be destroyed, allowing the core to collapse to form a black hole. For even larger stars, models predict that no supernova occurs and the star collapses directly to the black hole stage.



X-ray: NASA/CXC/SAO/FSeward; Optical: NASA/ESA/ASU/J.Hester & A.Loll; Infrared: NASA/JPL-Caltech/Univ. Minn./R.Gehrz

Figure 8.10 The Crab Nebula is located in the constellation Taurus the Bull, just where Chinese astronomers saw a brilliant guest star in the year 1054 CE. High-speed electrons produced by the central neutron star spiral through magnetic fields and produce the foggy glow of synchrotron radiation that fills the nebula. This image of the Crab Nebula, combining visible, infrared, and X-ray light, reveals the neutron star, a disk of hot gas more than 1 ly across and a curving jet.

type I supernova A supernova explosion that displays no hydrogen lines in its spectrum. It can be the explosion of a white dwarf star or a massive star whose hydrogen-rich outer layers have been previously removed.

type II supernova A supernova explosion caused by the collapse of a massive star, showing prominent hydrogen spectral lines.

Types of Supernovae

Supernovae come in several types. The two main types are distinguished by features in their spectra. **Type I supernovae** are those that don't show hydrogen lines in their spectra. We've already encountered the type Ia subtype, which are the white-dwarf supernovae. They don't show hydrogen spectral lines because most of the exploding material is carbon and oxygen. **Type II supernovae** *do* show hydrogen spectral lines. They result from the collapse of a massive star once it has developed an iron core, as just described. At the time of explosion, such stars still possess many solar masses of unprocessed hydrogen gas, so their spectra show hydrogen lines. Other type I subtypes, such as type Ib and Ic, are also believed to result from the collapse of massive stars that have already lost their hydrogen-rich outer layers before they explode, perhaps through interactions with a binary companion.

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Different types of supernovae can also be distinguished by the rate at which their brightness decreases. Type II decrease in brightness at the same rate at which radioactive nickel and cobalt decay. This is evidence for the production of heavy elements during type II supernovae.

Observations of Supernovae

In the year 1054 CE, Chinese astronomers saw a "guest star" appear in the constellation known in the West as Taurus the Bull. The star quickly became so bright it was visible in the daytime, then faded slowly over the next two years. When modern astronomers turned their telescopes to the location of the guest star, they found a peculiar nebula now known as the Crab Nebula for its many-legged shape (see Figure 8.10). In fact, the legs of the Crab Nebula are filaments of gas that are moving away from the site of the explosion at about 1400 km/s. Comparing the radius of the nebula, 4.4 ly, with its velocity of expansion reveals that the nebula began expanding nine or ten centuries ago, just when the guest star made its appearance. The Crab Nebula is clearly the remains of the supernova seen in 1054 CE. The next section describes the neutron star found at the centre of the Crab Nebula.

The blue glow of the Crab Nebula is produced by synchrotron radiation. This form of electromagnetic radiation, unlike blackbody radiation, is produced by rapidly moving electrons spiralling through magnetic fields and is common in the nebulae produced by supernovae. In the case of the Crab Nebula, the electrons travel so fast they emit visible wavelengths of light. In most such nebulae, the electrons move slower, and the synchrotron radiation is at radio wavelengths.

Supernovae are rare. While astronomers using robotic telescopes catch several thousand of them a year happening across the cosmos, only a handful have ever been seen with the naked eye. Arab astronomers saw one in 1006 CE, and the Chinese and the Anasazi in North America saw one in 1054 CE. European astronomers observed two—one in 1572 CE (Tycho's supernova) and one in 1604 CE (Kepler's supernova).

On the morning of February 24, 1987, Canadian astronomer Ian Shelton and his Chilean colleague Oscar Duhalde entered the ranks of the lucky few who have ever spotted a supernova visible to the naked eye. They were working at the Las Campanas Observatory high in the Andes Mountains in northern Chile when they noticed a new star in the sky. It turned out to be a supernova, shining brightly from 163 000 light-years away in the Large Magellanic Cloud (LMC), a satellite galaxy orbiting our own Milky Way. This supernova, called SN 1987A (Figure 8.11), represents the first visual sighting of a supernova in 383 years. It has given astronomers a ringside seat for the most spectacular event in stellar evolution.

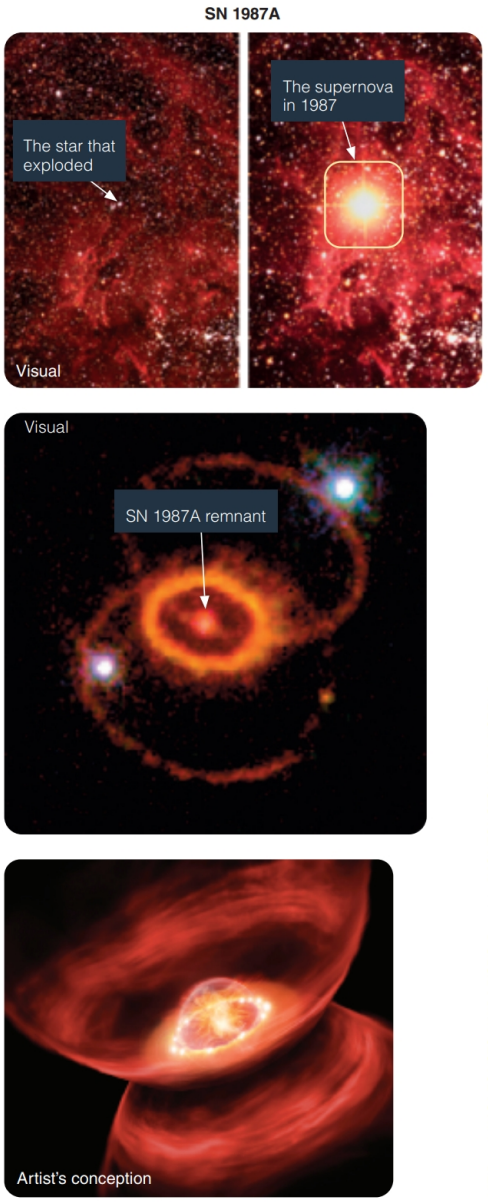


Figure 8.11 Supernova 1987A was produced by the explosion of a 20-solar-mass star. The bright ring is about 1 ly in diameter and composed of gas ejected about 20 000 years ago. It is being excited to glow as it is hit by a shock wave from the explosion. The fainter rings are produced by the flash of light from the explosion illuminating gas that was previously ejected. The two bright stars are not associated with the supernova.

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Nearly four hours before the supernova was first seen, a blast of neutrinos were picked up by detectors in Japan, the United States, and Russia. The neutrinos were later confirmed to have arrived from the direction of SN 1987A. They were likely produced when the iron core of the progenitor star collapsed, smashing its electrons into its protons to produce neutrons and neutrinos, as described previously. An urgent alert circulated by Shelton and Duhalde allowed many large telescopes to catch the supernova in its early stages, and it has been studied intensely ever since. Analysis of archival observations of the LMC have allowed the progenitor of the supernova to be identified and characterized.

SN 1987A was a type II supernova but, as shown in Figure 8.12, its light curve is not typical. Typical

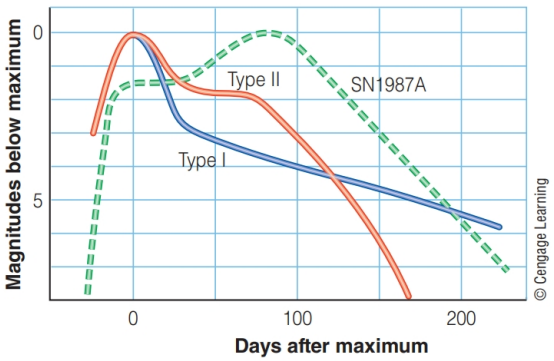


Figure 8.12 Type I supernovae decline in brightness rapidly at first and then more slowly, but type II supernovae pause for about 100 days before beginning a steep decline. Supernova 1987A was odd in that it did not rise directly to maximum brightness. These light curves have been adjusted to the same maximum brightness.

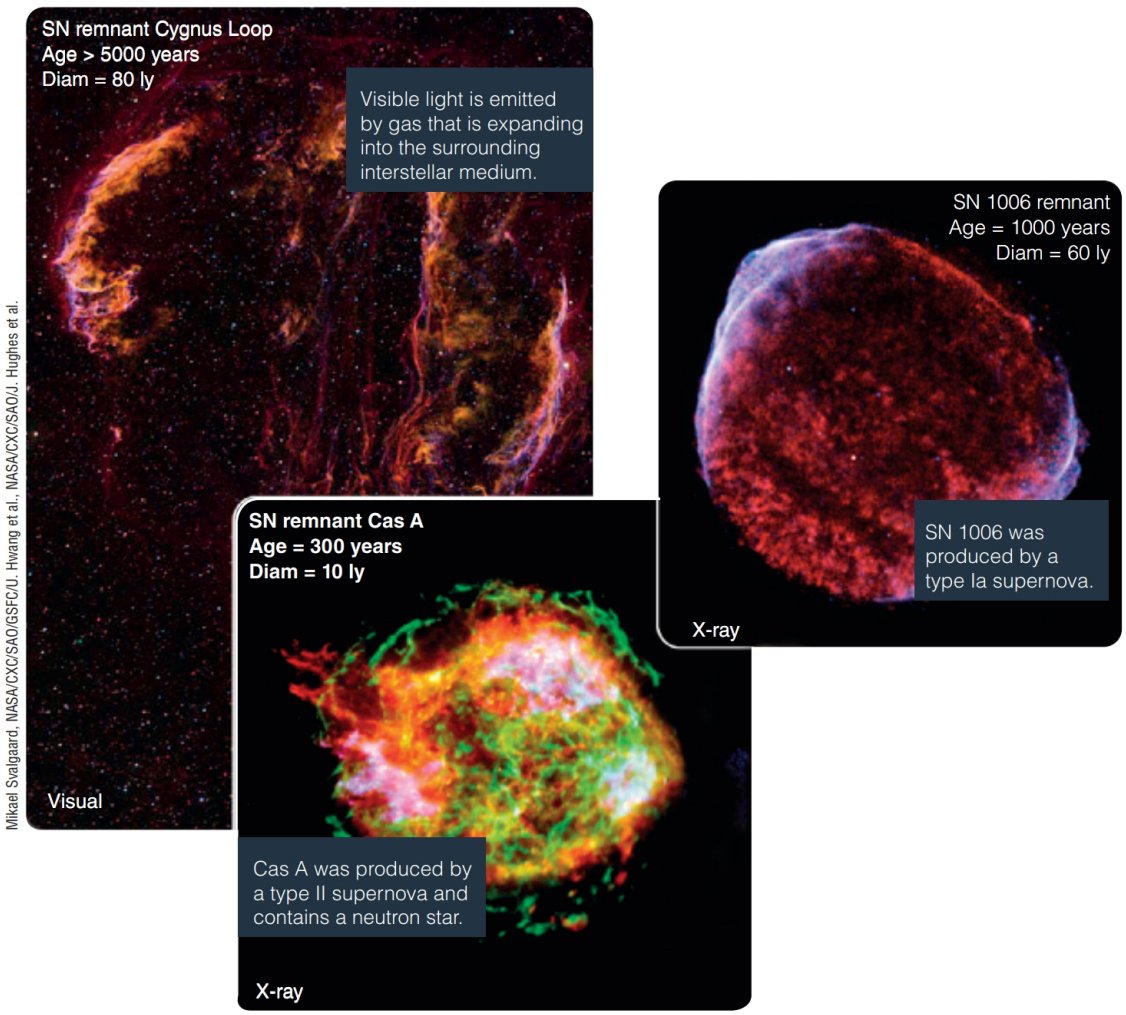


Figure 8.13 A supernova remnant is an expanding bubble of hot gas created by a supernova explosion. As the remnant expands and pushes into neighbouring gas, it can emit radiation at many wavelengths.

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white-dwarf supernovae (type Ia) are more luminous at maximum brightness, decline rapidly at first, and then more slowly. Typical core-collapse (type II) supernovae are not as bright at maximum, and they decline in a more irregular way. Our models indicate that most type II supernovae are caused by the collapse of red supergiants, but SN 1987A was produced by the explosion of a hot, blue supergiant. Astronomers hypothesize that this star was once a red supergiant but later contracted and heated up slightly, becoming bluer before it exploded.

Although a supernova explosion fades to obscurity in a year or two, an expanding shell of gas marks the site of the explosion. The gas, originally expelled at 10 000 to 20 000 km/s, may carry away a fifth of the mass of the star. The collision of that expanding gas with the surrounding interstellar medium can sweep up even more gas and excite it to produce a **supernova remnant**, the nebulous remains of a supernova explosion. Figure 8.13 shows images of three supernova remnants of different ages, showing how they expand and become more diffuse over time.

Supernova remnants look quite delicate and do not survive very long—a few tens of thousands of years—before they gradually mix with the interstellar medium and vanish. The Crab Nebula is a young remnant, only about 950 years old and about 8.8 ly in diameter. Older remnants can be larger. Some supernova remnants are visible only at radio and X-ray wavelengths. They have become too tenuous to emit detectable light at visible wavelengths, but the collision of the expanding hot gas with the interstellar medium can generate radio and X-ray light. You learned in Chapter 7 that the compression of the interstellar medium by expanding supernova remnants can also trigger star formation.

supernova remnant The expanding shell of gas and dust marking the site of a supernova explosion.

neutron star A small, highly dense star, with radius about 10 km, composed almost entirely of tightly packed neutrons.

8.5 Neutron Stars

What remains after the supernova explosion of a massive star? There are several options: a neutron star, a black hole, or perhaps only an expanding cloud of debris. A **neutron star** contains a little over 1 solar mass

CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



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Ian Shelton with the telescope used in Sn19 87A discovery

Ian Keith Shelton

In 1987, Winnipeg-born Ian Keith Shelton discovered the first supernova visible to the naked eye since Johannes Kepler saw supernova SN 1604 almost 400 years earlier. After receiving his B.Sc. from the University of Manitoba in 1979, Shelton worked at the University of Toronto's Southern Observatory at Las Campanas, Chile. On February 24, 1987, while he was in Chile, Shelton noticed a bright light on a photograph of a nearby galaxy called the Large Magellanic Cloud. Thinking the photo was flawed, he walked outside to check the sky with the naked eye and confirmed his amazing discovery. It was light from a star born 11 million years ago that had exploded 163 000 years ago. Shelton and another observer, Oscar Duhalde, also at Las Campas Observatory, reported the observation via telegram to the International Astronomical Union's Central Bureau for Astronomical Telegrams. They were credited with the discovery, together with Albert Jones who independently reported the event from New Zealand. The news of the discovery spread rapidly, and almost every telescope in the southern hemisphere was immediately turned toward this grand occurrence in the sky. Thanks to its early detection, this supernova designated SN 1987A is the most well-observed supernova in history. Since its launch in 1990, the Hubble Space Telescope has regularly monitored the supernova remnant. Shelton became a graduate student at the University of Toronto in the fall of 1987. He received his M.Sc. in 1990 and Ph.D. in 1996. He has since worked as an astronomer at several observatories, including Japan's 8.3-metre Subaru Telescope in Hawaii, the 1.9-m David Dunlap Observatory in Toronto, Athabasca University north of Edmonton, and the 6.5-m MMT Observatory south of Tucson. The asteroid Shelton is named in his honour.

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compressed to a radius of about 10 km. Its density is so high that only the immense power of neutron degeneracy pressure can stop it from collapsing to become a black hole. What's the evidence that such strange objects actually exist?

Theoretical Prediction of Neutron Stars

The subatomic particles called neutrons were discovered in a laboratory in 1932. Physicists quickly realized that neutrons, like electrons, were subject to degeneracy pressure that would allow them to form nearly incompressible fluids. Just two years later, in 1934, astronomers Walter Baade and Fritz Zwicky suggested that some of the most luminous novae in the historical record were not regular novae but were caused by the collapse and explosion of massive stars in a type of cataclysm they named a "super-nova." Zwicky termed the hypothetical remnant—a ball of degenerate neutrons the size of a city—a "neutron star."

Mathematical models predict that a neutron star is only 20 or so kilometres in diameter and has a density of about 10^{14} g/cm^3. That is roughly the density of atomic nuclei, so you can think of a neutron star as matter with all the empty space squeezed out of it. A sugar-cube-sized lump of this material would have a mass of 100 million tons, the mass of a small mountain.

Simple physics predicts that neutron stars (1) spin rapidly, perhaps 100 to 1000 rotations per second; (2) are hot, with surface temperatures of millions of degrees K; and (3) have strong magnetic fields, up to a trillion times stronger than the Sun's or Earth's magnetic fields. The rapid spin rate is a simple consequence of the conservation of angular momentum: collapsing the core of a relatively slowly rotating massive star would cause its spin rate to increase dramatically, just like a spinning figure skater. Other processes during core collapse would likely create high temperatures and strong magnetic fields. Despite their high temperature, neutron stars would be difficult to detect because of their tiny size—recall that the luminosity of an object depends not only on its surface temperature, but also its size.

Physicists are still struggling to understand the properties of pure neutron matter. It can't be made in a laboratory, so models must substitute for laboratory experiments. These models suggest that neutron stars have a maximum mass, similar to the Chandrasekhar mass for white dwarfs. The limiting mass for a neutron star is probably about 2 to 3 solar masses. An object more massive than that can't be supported by neutron degeneracy pressure, so it would collapse and presumably become a black hole.

pulsar A source of short, precisely timed radio bursts, understood to be spinning neutron stars.

The Discovery of Pulsars

In November 1967, Jocelyn Bell, a graduate student at Cambridge University in England, found a peculiar pattern in the data from a radio telescope. Unlike other radio signals from celestial bodies, this was a series of regular pulses (see Figure 8.14). At first she and the leader of the project, Anthony Hewish, thought the signal was interference from a source on Earth, but they found it day after day at the same celestial latitude and longitude. Clearly, it was cosmic in origin.

Another possibility, that it came from a distant civilization, led them to consider naming it LGM, for Little Green Men. Within a few weeks, the team found three more objects in other parts of the sky pulsing with different periods. The objects were clearly natural, and the team dropped the name LGM in favour of **pulsar**—a "pulsing star." The pulsing radio source Bell had observed with her radio telescope was the first known pulsar. Hewish received the 1974 Nobel Prize in physics for this work, while Bell was excluded from recognition.

As more pulsars were found, astronomers argued over their nature. The pulses, which typically last only about 0.001 second, gave astronomers an important clue. The pulse length places an upper limit on the size of the object producing the pulse. This is a very important principle in astronomy: an object cannot change its brightness significantly in an interval shorter than the time light takes to cross its diameter. If pulses from pulsars are no longer than 0.001 second, the objects cannot be larger

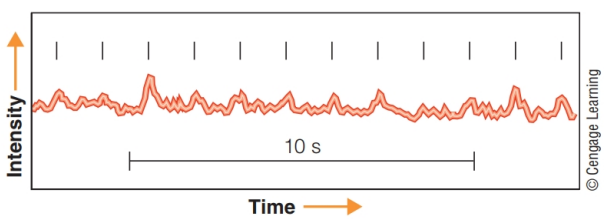


Figure 8.14 The 1967 detection of regularly spaced pulses in the output of a radio telescope led to the discovery of pulsars. This record of the radio signal from the first pulsar, CP1919, contains regularly spaced pulses (marked by ticks). The period is 1.3373 seconds.

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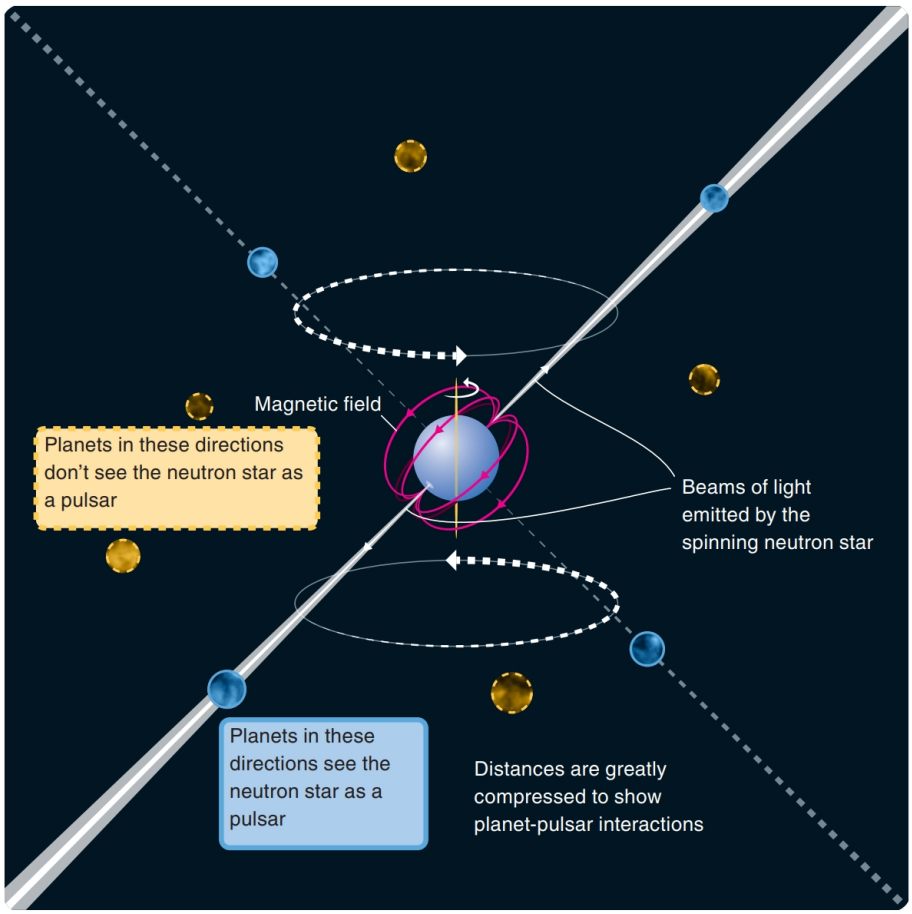


Figure 8.15 A neutron star contains a powerful magnetic field and spins very rapidly. The spinning magnetic field generates a tremendously powerful electric field, and the field causes the creation of electron-positron pairs that accelerate through the magnetic field, emit photons in the directions of their motion, and thereby produce powerful beams of electromagnetic radiation emerging from the neutron star's magnetic poles.

than 0.001 light-second—or 300 km—in diameter, which is smaller than the diameter of white dwarfs. This makes neutron stars the only reasonable explanation.

The missing link between pulsars and neutron stars was found in late 1968, when astronomers discovered a pulsar at the heart of the Crab Nebula (see Figure 8.10). The Crab Nebula is a supernova remnant, which agrees nicely with Zwicky and Baade's prediction that some supernovae should produce a neutron star. The short pulses and the discovery of the pulsar in the Crab Nebula are strong evidence that pulsars are neutron stars.

The modern model of a pulsar, which has been called the **lighthouse model**, is illustrated in Figure 8.15. In a sense the name *pulsar* is inaccurate: A pulsar does not turn off and on in pulses. Rather it emits beams of light that sweep around the sky as the neutron star rotates, like a rotating lighthouse light. The mechanism that produces the beams involves extremely high energies and strong electric and magnetic fields and is not fully understood. There are pulsars, called *magnetars*, with unimaginably strong magnetic fields—more than 1000 trillion times stronger than Earth's magnetic field. Around 3000 pulsars have been discovered, but many more neutron stars are out there, undetected because their beams never point toward Earth.

The Evolution of Pulsars and Neutron Stars

When a pulsar first forms, it may be spinning as many as 100 times a second. As it radiates energy into space, its rotation slows. This causes a measurable increase in the time interval between pulsar pulses. Judging from the rates at which their rotation slows down, the average pulsar is apparently only a few million years old, and the oldest has an age of about 10 million years. Presumably, neutron stars older than that rotate too slowly to generate detectable radio beams. Supernova remnants last only about 50 000 years before they mix into the interstellar medium and disappear, so most pulsars have long outlived the remnants in which they were originally embedded.

The neutrino burst released by supernova 1987A in February 1987 suggests it formed a neutron star. As of this writing, no neutron star has been detected in the SN 1987A remnant, but astronomers continue to watch the site hoping to find the youngest pulsar known. Alternatively, it's possible

lighthouse model The explanation of a pulsar as a spinning neutron star sweeping beams of electromagnetic radiation around the sky.

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that SN 1987A didn't produce a neutron star at all. It may have reabsorbed some of the material initially ejected and collapsed to form a black hole. Some theories even predict the existence of more bizarre forms of compact stars, made not of neutrons, but of the particles that make up neutrons, called quarks. So far, there is little observational evidence for these hypotheses, but they remain intriguing.

8.6 Black Holes and Relativity

We have seen that sunlike stars collapse to form white dwarfs, supported by the degeneracy pressure of their electrons, and more massive stars collapse to form neutron stars, supported by neutron degeneracy pressure. But what of truly gigantic stars, whose immense gravity is enough to overcome neutron degeneracy pressure and force the star to collapse past the neutron star stage? In such cases, the remnant of the star collapses until it is so extremely dense that it pinches itself off from the rest of the cosmos in a pocket of highly warped space and time called a black hole.

A complete understanding of the physics of black holes requires sophisticated mathematics, but we can get an idea of why they ought to exist by considering a simple question: how fast must an object travel to escape from the surface of a celestial body? The answer leads to black holes.

Escape Velocity

In Chapter 3 you learned that the escape velocity is the initial velocity an object needs to escape the gravity of another object. If you were on the surface of Earth and you wanted to throw a baseball hard enough that it would fly into space and never return, you'd have to throw it at about 11 km/s. But if you threw the same baseball from the top of a tall tower, you could throw it a little slower and it would still escape Earth's gravity. That's because an object's escape velocity decreases the farther you get from its centre of mass. Escape speed also decreases with the mass of the object you're trying to escape from, so it's easier to escape from the gravity of an asteroid than the gravity of Earth.

But what happens as you *increase* the mass of the object you're trying to escape from? Eventually the escape velocity would exceed the speed of light. To understand what happens as the speed of an object approaches the speed of light, we need to explore Einstein's theory of relativity.

Special Relativity and Space-Time

In 1905, Albert Einstein published four remarkable scientific papers that changed the way we looked at everything from atoms to galaxies. One of his insights concerns the fundamental nature of space and time. It begins with a deceptively simple question: What does it mean for something to be "moving"?

In ordinary language, we say things like "An airplane flies at 900 km/h." We mean that it would take the airplane one hour to fly between two cities 900 km apart. We intuitively understand that the speed is being stated *relative to the ground*—or, to put it another way, that the ground is our *frame of reference*. We aren't usually explicit about our frames of reference, assuming that everyone will choose the same ones. However, if we are very careful to specify our frames of reference, we come to some startling insights about the nature of space and time.

Imagine your friend Ameera is sitting a few rows behind you on an airplane flying at 900 km/h. If we say that Ameera tosses a ball toward you at 10 km/h, we intuitively understand this to mean that the ball moves at 10 km/h *relative to the plane.* The plane is the frame of reference. However, someone on the ground could just as well use the ground as their frame of reference. They would say that the ball moves at 10 km/h relative to the plane and the plane moves at 900 km/h relative to the ground, so the ball must be moving at 910 km/h relative to the ground. Whether we say the ball is flying at 10 km/h or 910 km/h is a matter of our choice of reference frame.

Even prior to Einstein, physicists such as Hendrik Lorentz realized that there was something wrong with the way we added speeds in the previous example. To get the speed of the ball relative to the ground, we added the speed of the ball relative to the plane to the speed of the plane relative to the ground. This method of adding speeds is accurate enough for objects moving at the ordinary day-to-day speeds of baseballs and airplanes. However, starting in the late 1800s, physicists realized that this way of adding speeds *disagreed* with measurements of motion at or near the speed of light.

In a famous 1887 experiment, physicists Albert A. Michelson and Edward W. Morley attempted to measure

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the difference in speed between light rays aimed in the directions parallel and perpendicular to Earth's motion through space. According to our airplane example, the speed of a light ray moving in the same direction as Earth should be increased by the speed at which Earth itself is moving, while the light ray moving in the perpendicular direction should be unaffected. And yet, no matter how they measured, Michelson and Morley could not detect any difference in the speed of light rays aimed in different directions. This gave a hint that there was something peculiar about the motion of light.

Einstein's great insight was that motion could be correctly described by observers in any reference frame if all observers agree on two things: the laws of physics and the speed of light. It probably seems reasonable that the laws of physics shouldn't change just because you're moving. But if our airplane example is correct, then observers measuring the motion of light relative to different frames of reference should get different answers. So why don't they? Why should the speed of light be the same to all observers in all frames of reference?

Imagine that in the previous example the pilot of the airplane fires a laser beam out the front window of the plane. The pilot measures the laser light to be travelling away from her at the speed of light, which is 300 000 km/s. Our intuition is that someone on the ground should measure the light ray to be moving at 300 000 km/s plus 900 km/h. Einstein discovered that this is wrong, that *both* the pilot and the person on the ground should measure the light ray to be moving at 300 000 km/s, whether measured relative to the ground or the plane!

This is deeply weird. How can the ball have different speeds in different reference frames while light has the same speed in all reference frames? The answer has to do with how space and time are put together. Living our lives at speeds far below the speed of light, it seems to us like there is an "absolute frame of reference" against which all distances can be measured. We also imagine a "cosmic clock" that ticks the same time for all points in the universe. Einstein showed that neither of these ideas is correct. Neither space nor time are "absolute" quantities, the same for all observers. The distance a moving object travels and the time it takes to travel that distance are dependent on who is doing the measuring. The true "absolute" is the speed of light.

Einstein's two postulates—the universality of the laws of physics and the invariance of the speed of light—form the basis for his *special theory of relativity*. Special relativity predicts two truly bizarre phenomena, alien to our everyday experience: **time dilation** and length contraction.

Let's return to our previous question: how can the speed of light be the same in all reference frames? Imagine that you and Ameera set up an experiment on the airplane. You lay a metre stick along the aisle and fire a laser beam along it. Timing how long it takes the laser beam to traverse the metre stick, you find it takes 3.34 nanoseconds. Now imagine that someone on the ground makes the same measurement. Measuring relative to a metre stick on the ground, the person on the ground would find that the metre stick on the plane is *less than 1 m long* and the light traverses it in *less than 3.34 nanoseconds*. Yet, when you on the plane and the person on the ground divide your distance measurements by your time measurements, you would *both* find that the light had travelled at the same speed during the experiment—300 000 km/s.

You might think that there is some kind mistake here, or a disagreement about terminology. Perhaps we are not timing our measurements correctly, or we are confusing *perceived* differences with *real* ones. Let us be clear: we are saying that, relative to the ground, distances on the plane *really are* shorter and time on the plane *really does* flow slower. These effects are called length contraction and time dilation. They arise any time two objects are moving relative to one another, at any speed. They become perceptible only when those speeds approach the speed of light, but they can be measured at ordinary speeds. For example, we can take two precisely synchronized clocks, leave one on the ground and send the other flying in an airplane. When the two clocks are reunited, the one that travelled on the plane has recorded the passage of less time than the one on the ground, in proportion to how fast the plane flew. Moving clocks really do run slow.

Einstein's special theory of relativity does away with notions of time and space as separate, absolute quantities. In the full view of space and time, as described in Einstein's **general theory of relativity**, space and time are bound together into a single entity called "space-time." Space-time bends and shapes itself in such a way that all observers agree on the speed of light. As we shall see, the remnants of dead stars cause space-time to bend in extreme ways, giving rise to many strange phenomena.

time dilation The slowing of moving clocks or clocks in strong gravitational fields.

general theory of relativity Einstein's theory describing how space and time are bound together into "space-time."

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HOW DO WE KNOW? 8.1

Theories and Proof

No scientific theory or hypothesis can be proved absolutely correct. You can test a hypothesis over and over by performing experiments or making observations, but you can never prove that the hypothesis is absolutely true. It is always possible that you have misunderstood the hypothesis or the evidence, and the next observation you make might disprove the hypothesis.

For example, you might propose the hypothesis that the Sun is mostly calcium and iron vapour because those elements are known to be abundant on Earth. You might test the hypothesis by searching for calcium and iron lines in the solar spectrum, and the strength of the lines would suggest your hypothesis is correct. Although your observation has confirmed your hypothesis, it has not proven the hypothesis is absolutely true. You might confirm the hypothesis many times in many ways before you realize that at the temperature of the Sun's surface, iron and calcium atoms absorb photons much more efficiently than hydrogen, creating strong spectral lines. Although the hydrogen lines are weak in the Sun's spectrum, a careful analysis shows that most of the atoms in the Sun are hydrogen, not iron or calcium.

The nature of scientific thinking can lead to misconceptions about how science works. Some people think that scientists don't really know anything because scientific ideas can be overturned by new evidence. What scientists actually have is a model of reality that gets more accurate with every test. A model that has survived many tests "graduates" to being considered a theory, but it must still be revised in the light of new evidence.

Sometimes people misinterpret the language of "theories" and "laws," particularly when they say that something is "only a theory." Scientists sometimes label well-tested theories as laws, but this can give an inaccurate impression that these laws are not subject to further testing. We sometimes speak of Newton's law of gravity, which suggests that it is the final word on gravity. Yet we have known for a century that Einstein's "theory" of general relativity is a better explanation for gravity than Newton's "law." We already know that general relativity is itself incomplete and will need to be replaced by an even more comprehensive theory someday. So, scientists prefer to use the language of "theories" to emphasize that science is subject to continual revision in the light of new evidence.



SOHO/MDI

Technically it is still a theory, but astronomers have great confidence that the Sun is mainly composed of hydrogen.

Schwarzschild Black Holes

What can relativity tell us about the deaths of massive stars? If the core of a collapsing star contains more than about 3 solar masses, nothing can stop the collapse, not even degeneracy pressure. As the core contracts, its mass remains constant but its size decreases, so the escape velocity at its surface increases. When the escape velocity exceeds the speed of light, the core finds itself in a very strange situation. Because light is the fastest thing in the universe, once the escape velocity exceeds the speed of light, nothing can ever escape the dead core of the star. It is permanently sealed off in a pocket of space that objects and light can enter but never leave. We call such objects **black holes**. Note that a black hole is a spherical region of space, within which the escape velocity is greater than the speed of light.

What happens to the core of the star as it collapses? If no known force can stop it from collapsing, perhaps it collapses to zero size and becomes what mathematicians call a **singularity**. Some theorists think that a singularity is impossible and that the laws of quantum physics must somehow halt the collapse. Astronomically, it seems to make little difference.

black hole A mass that has collapsed to such a high density that its gravity prevents the escape of all matter and energy from a large volume of space around it.

singularity An object of zero radius and infinite density.

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Einstein's general theory of relativity and Newton's theory of gravity give different descriptions of gravity, and therefore different descriptions of black holes. Rather than imagining gravity as a force that passes through space, as in Newton's theory, relativity imagines gravity as a consequence of the curvature of space-time. According to general relativity, planets follow their orbits around the Sun because the Sun creates a "dimple" in space-time in which the planets are trapped. You can think of the planets as small beads rolling around on the inside of a frictionless funnel: the Sun's enormous mass bends space-time, creating the funnel, and the planets are the beads trapped inside.

Shortly after the publication of Einstein's general theory of relativity, which describes how mass bends space-time, astronomer Karl Schwarzschild found a way to solve the equations of relativity to describe the gravitational field around a single, nonrotating, electrically neutral lump of matter. Schwarzschild's solution shows that if matter is packed into a small enough volume, space-time adopts extreme curvature and becomes a black hole. Objects can still follow paths that lead into it, but no path leads out, so nothing can escape, not even light. Consequently, the inside of the black hole is totally beyond the view of an outside observer. The **event horizon** is the boundary between this isolated volume of space-time and the rest of the universe. The radius of the event horizon is called the **Schwarzschild radius, R_S**—the radius within which an object must shrink to become a black hole (Figure 8.16). The event horizon is the sphere of no return for any object falling in later.

According to Schwarzschild's calculations, the size of a black hole, its Schwarzschild radius, is simply proportional to its mass. A 3-solar-mass black hole will have a Schwarzschild radius of about 9 km. Note that even a very massive black hole would not be very large. The largest of them are approximately the size of the solar system, which is still fairly small in astronomical terms.

It is a common misconception to think of black holes as giant vacuum cleaners that suck up everything in the universe. A black hole is just a powerful gravitational field (or, in the relativistic view, a volume of highly curved space-time). At a large distance its gravity is no greater than that of a normal object of similar mass. If the Sun were replaced by a 1-solar-mass black hole, the orbits of the planets would not change at all. The gravity of a black hole becomes extreme only when an object approaches close to it. Figure 8.17 illustrates this by representing gravitational fields as curvature of the fabric of space-time. Physicists like to graph the strength of gravity around a black hole as curvature in a flat sheet. The graphs look like funnels in which the depth of the funnel indicates the strength of the gravitational field, but black holes themselves are not shaped like funnels; they are spheres or spheroids. Note that in Figure 8.17 the strength of the gravitational field around the black hole becomes extreme only if an object ventures too close.

This chapter has focused on black holes that could originate from the deaths of massive stars. In later chapters, you will encounter black holes located in the centres of galaxies whose masses can reach billions of solar masses.

Leaping into a Black Hole

Before you can search for real black holes, you must understand what theory predicts about the behaviour of a black hole. To explore that idea, imagine that you leap, feet first, into a Schwarzschild black hole.

If you were to leap from a distance of an astronomical unit into a black hole of a few solar masses, the gravitational pull would not be very large at first, and you would fall slowly. Of course, the longer you fell and the closer you came to the centre, the faster you would travel. Your wristwatch would tell you that you fell for about two months before you reached the event horizon.

Your friends who stayed behind would see something different. They would see you falling more slowly as you came closer to the event horizon because, as described by general relativity, time *dilates* or slows down in curved space-time. In fact, your friends would never actually see you cross the event horizon. To them, you would fall more and more slowly until you seemed hardly to move. Generations later, your descendants could focus their telescopes on you and see you still inching closer to the event horizon. You, however, would have sensed no slowdown and would conclude that you had crossed the event horizon after about two months.

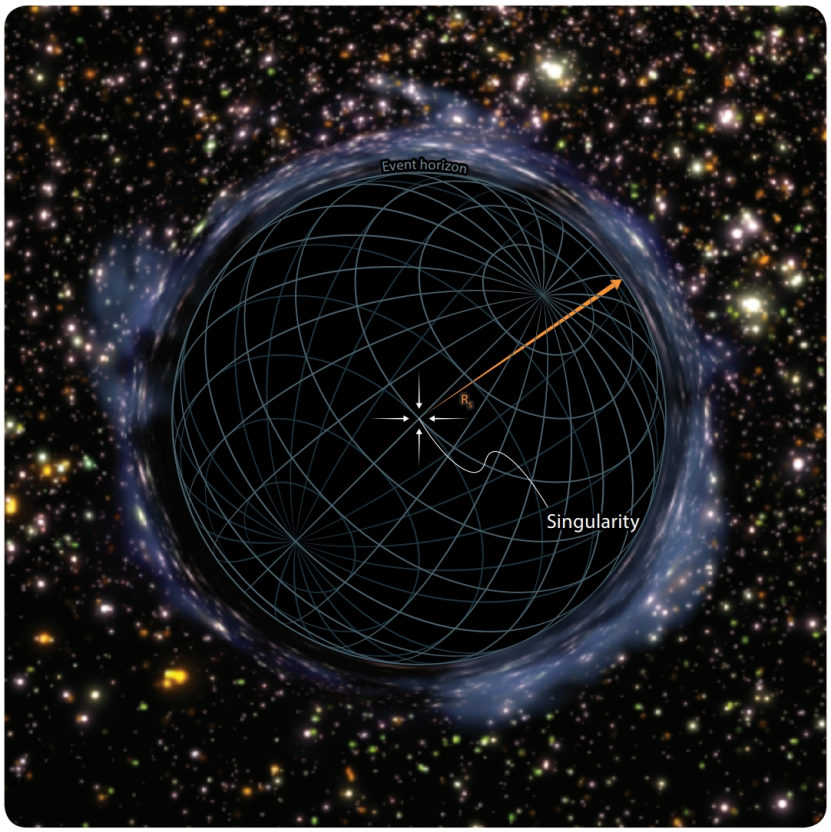
Another relativistic effect would make it difficult to see you with normal telescopes. As light travels out of a gravitational field, it loses energy, and its wavelength grows longer. This is known as the **gravitational redshift**. Although you would notice

event horizon The boundary of the region of a black hole from within which no matter or energy may escape. No event that occurs within the event horizon is visible to a distant observer.

Schwarzschild radius (R_s) The radius of the event horizon around a black hole.

gravitational redshift The lengthening of the wavelength of a photon as it escapes from a region of curved space-time gravitational redshift.

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Figure 8.16 A black hole forms when an object collapses to a small size (perhaps to a singularity) and the escape velocity becomes so great light cannot escape. The boundary of a black hole is called the event horizon because any event that occurs inside is invisible to outside observers. The radius of the black hole R_S is the Schwarzschild radius.

no effect as you fell toward the black hole, your friends would need to observe at longer and longer wavelengths in order to detect you.

While these relativistic effects seem merely peculiar, other effects would be quite unpleasant. Imagine again that you are falling feet first toward the event horizon of a black hole. You would feel your feet, which would be closer to the black hole, being pulled in more strongly than your head. This is a tidal force. At first it would be minor, but as you fell closer it would become very large. Another tidal force would compress you as your left side and your right side both fell toward the centre of the black hole. For any black hole with a mass comparable to a star, the tidal forces would be fatal long before you reached the event horizon (Figure 8.18).

The Search for Black Holes

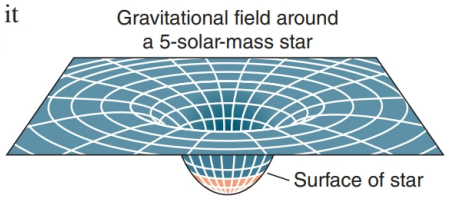
If black holes are totally black, how can we be sure they exist? A totally isolated black hole would be completely invisible, because it emits no light and any light falling upon it would be trapped within the event horizon. Fortunately, many black holes are not isolated and can be detected indirectly. Consider a binary star system in which one of the stars dies and becomes a compact object—a neutron star or a black hole. The compact object can attract material from the other star. Conservation of angular momentum dictates that the infalling material will form a disk around the compact object. Conservation of energy ensures that the disk will be heated to millions of degrees by collisions among its particles. This extremely hot accretion disk will emit X-rays, which is why we call these systems X-ray binaries. By studying the orbital properties of the system, we can use Kepler's laws to determine the mass of the compact object. If it is greater than about 3 solar masses, it cannot be a neutron star and must be a black hole.

The X-rays being emitted by X-ray binary systems containing a black hole are not being emitted by the black hole itself. Nothing can escape from a black hole. These X-rays are being emitted by hot material as it spirals toward the event horizon. The first X-ray binary suspected of harbouring a black hole was Cygnus X-1 (see **Canada's Role in the Global Story of Astronomy** in Chapter 10). It contains a supergiant star of spectral type B0 and a compact object orbiting each other with a period of 5.6 days. Matter flows from the B0 star and enters a hot accretion disk around the compact object (Figure 8.19). The accretion disk's inner few hundred kilometres have a temperature of about 2 million Kelvin—hot enough to radiate X-rays. The compact object is invisible, but Doppler shifts in the spectrum reveal the motion of the B0 star around the centre of mass of the binary. From the geometry of the orbit, astronomers have calculated the mass of the compact object to be at least 3.8 solar masses, well above the maximum for a neutron star.

As X-ray telescopes have located more X-ray objects, the list of stellar-mass black hole candidates has grown into the dozens. Some of these objects are shown in Table 8.2. Each candidate is a compact object surrounded by a hot accretion disk in a close X-ray binary system without regular pulsations. A few of the binary systems

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are easier to analyze than others, but it has become clear that some of these objects are too massive to be neutron stars. The evidence is now overwhelming: black holes really do exist.



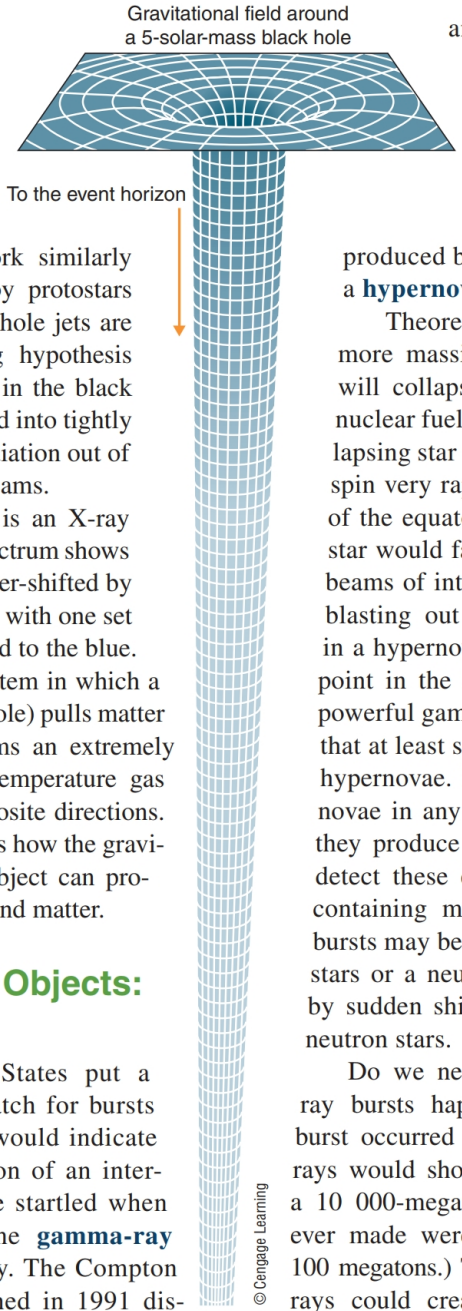


Figure 8.17 If a star and a black hole have the same mass, the force of gravity experienced at large distances from either one would be the same. The differences arise only at very close distances, where the space-time curvature of the black hole becomes extreme.

Energy from Compact Objects: Jets

Another way to detect the presence of a black hole is by the spectacular jets that they produce. The process isn't well understood but is thought to work similarly to the bipolar outflows ejected by protostars (Chapter 7), except that the black hole jets are far more powerful. The working hypothesis is that magnetic fields get caught in the black hole's accretion disk and are twisted into tightly wound tubes that squirt gas and radiation out of the disk and confine it in narrow beams.

One example of this process is an X-ray binary called SS 433. Its optical spectrum shows sets of spectral lines that are Doppler-shifted by about one-fourth the speed of light, with one set shifted to the red and one set shifted to the blue. Apparently, SS 433 is a binary system in which a compact object (probably a black hole) pulls matter from its companion star and forms an extremely hot accretion disk. Jets of high-temperature gas blast away in beams aimed in opposite directions. SS 433 is a prototype that illustrates how the gravitational field around a compact object can produce powerful beams of radiation and matter.

Energy from Compact Objects: Gamma-Ray Bursts

During the 1960s the United States put a series of satellites in orbit to watch for bursts of gamma rays from Earth that would indicate nuclear weapons tests in violation of an international treaty. The experts were startled when the satellites detected about one **gamma-ray burst** coming from space per day. The Compton Gamma Ray Observatory launched in 1991 discovered that gamma-ray bursts were occurring all over the sky, not grouped in any particular region. Starting in 1997, new satellites were able to detect gamma-ray bursts, determine their location in the sky, and immediately alert astronomers on the ground. When telescopes swivelled to image the locations of the bursts, they detected fading glows that resembled supernovae. This has led to the conclusion that some relatively long gamma-ray bursts are produced by a kind of supernova explosion called a **hypernova** (Figure 8.20).

Theoretical calculations indicate that a star more massive than about 15 or 20 solar masses will collapse and become a black hole when its nuclear fuel is exhausted. Models show that the collapsing star would conserve angular momentum and spin very rapidly, and this would slow the collapse of the equatorial parts of the star. The poles of the star would fall in quickly, and that would focus the beams of intense radiation and ejected gas that was blasting out along the axis of rotation—resulting in a hypernova. If either of those beams happens to point in the right direction, Earth would receive a powerful gamma-ray burst. The evidence seems clear that at least some gamma-ray bursts are produced by hypernovae. Massive stars rarely explode as hypernovae in any one galaxy, but the gamma-ray bursts they produce are so powerful that astronomers can detect these explosions over vast cosmic distances containing millions of galaxies. Some gamma-ray bursts may be produced by the merger of two neutron stars or a neutron star and a black hole, and others by sudden shifts in the crusts of highly magnetized neutron stars.

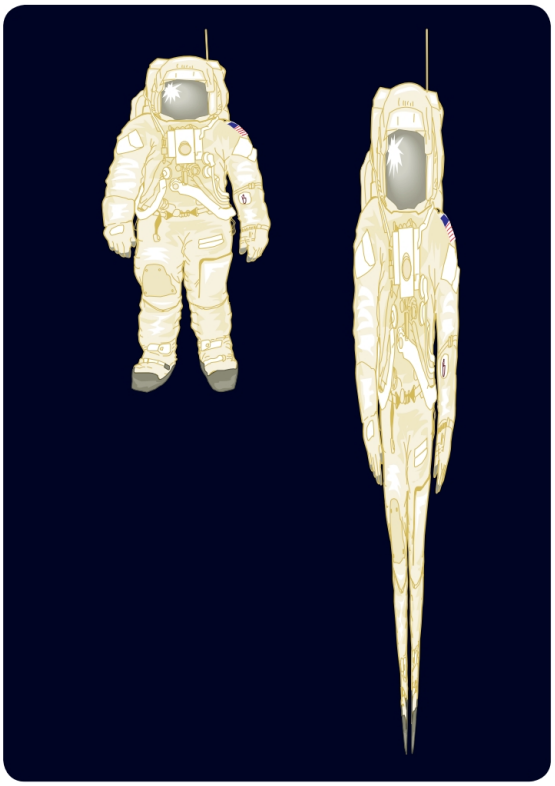
Do we need to worry about dangerous gamma-ray bursts happening near Earth? If a gamma-ray burst occurred only 1000 ly from Earth, the gamma rays would shower Earth with radiation equivalent to a 10 000-megaton nuclear blast. (The largest bombs ever made were less than 100 megatons.) The gamma rays could create enough nitric oxide in the atmosphere to produce intense acid rain and destroy the ozone layer, exposing life on Earth to

gamma-ray burst A sudden, powerful burst of gamma rays.

hypernova Produced when a very massive star collapses into a black hole; a possible source of gamma-ray bursts.

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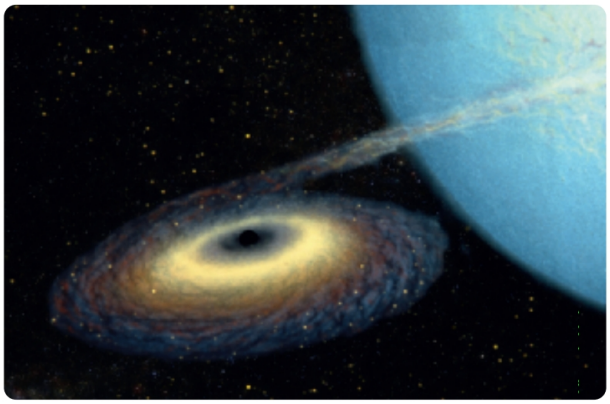
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Figure 8.18 Leaping feet first into a black hole. A person of normal proportions (left) would be distorted by tidal forces (right) long before reaching the event horizon of a typical stellar-mass black hole. Tidal forces would stretch the body lengthwise while compressing it laterally. Astrophysicists call this effect "spaghettification."

a deadly level of solar ultraviolet radiation. Although gamma-ray bursts are infrequent, they can occur relatively near Earth as often as every few hundred million years. These events could be one of the causes of the mass extinctions that show up in the fossil record and may have shaped the development of life on many planets.

Taking a Picture of a Black Hole

If black holes neither emit nor reflect light, is there any hope of actually taking a picture of one? In 2017, an international collaboration of more than 200 astronomers proved that the answer is yes. These astronomers combined their efforts and their telescopes to make the first-ever image of a black hole, as shown in Figure 8.21. The photo was made by combining millimetre-wavelength observations from telescopes in Mexico, Hawaii, Chile, Arizona, Spain, and Antarctica. By combining these telescopes together using a technique called interferometry, the astronomers



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Figure 8.19 The X-ray source Cygnus X-1 consists of a supergiant B star and a compact object orbiting each other. Gas from the supergiant's stellar wind flows into the hot accretion disk around the compact object, and astronomers detect X-rays from the disk.

were able to simulate a telescope nearly the size of Earth, which they call the Event Horizon Telescope (EHT). They targeted the supermassive black hole at the centre of the galaxy M87—a topic to which we will return in Chapter 10—because it is one of the few black holes large enough for the EHT to actually image. The astronomers knew that the first-ever picture of a black hole would be greeted skeptically, so they took great care to ensure that their results were accurate. The data were given to four separate teams that worked independently to produce four different images using different techniques. All of the images were very similar to one another, giving high confidence that the image is an accurate representation of a black hole. The precise way that light is seen to bend around the black hole is strong confirmation of Einstein's general theory of relativity.

Table 8.2 | Seven Black Hole Binaries

Object	Star	Orbital Period	Mass of Black Hole
Cygnus X-1	BOI	5.6 days	10 $M_\odot$
LMC X-3	B3V	1.7 days	>8 $M_\odot$
A0620-00	KV	7.75 hours	11 ± 1.9 $M_\odot$
V404 Cygni	G-KV	6.47 days	12 ± 3 $M_\odot$
GRO J1655-40	F5V	2.61 days	6.9 ± 1 $M_\odot$
QZ Vul	KV	8 hours	10 ± 4 $M_\odot$
4U 1543-47	AV	1.123 days	2.7 – 7.5 $M_\odot$

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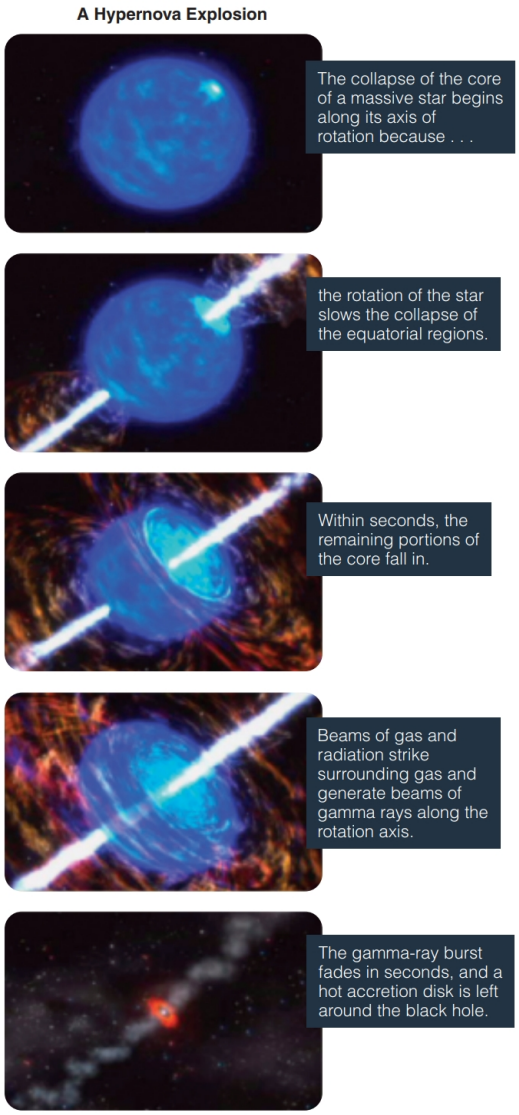


Figure 8.20 When an extremely massive star collapses in a hypernova explosion, energy from the core is focused into beams of radiation and matter that point along the axis of rotation. This is thought to be the source of gamma-ray bursts that last longer than two seconds.



Figure 8.21 A false-colour image of radio waves emitted by material surrounding the supermassive black hole at the centre of galaxy M87. The image does not show the event horizon of the black hole itself, but rather its "shadow." The shadow arises because of the way the highly distorted space-time around the black hole bends light emitted by nearby hot gas.

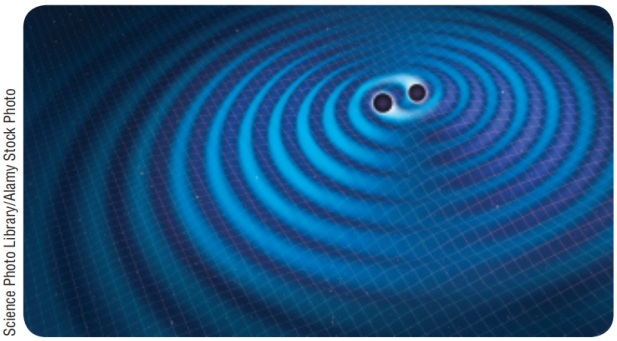


Figure 8.22 As a pair of black holes orbit in a binary system, they produce ripples in space-time that flow away from the system. These ripples can be detected from millions of light-years away.

8.7 Gravitational Waves

Compact objects do not sit at rest in the cosmos. They move around, often as members of binary systems. As they move, the "dimples" they produce in space-time move with them, creating ripples that flow away from them at the speed of light. The ripples are similar to the ones that would result if you dipped two fingers into the surface of a calm bath and made them orbit one another. As shown in Figure 8.22, the motion of these dimples creates "waves" in space-time that move away from the orbiting black holes. As you will learn in Chapter 11, these **gravitational waves** are very persistent and can be detected from millions or billions of light-years away. Gravitational waves give us yet another way to confirm the existence of compact objects and learn more about them.

On September 14, 2015, scientists operating a gravitational wave observatory in Louisiana registered a "chirp" in their detector, which consists of a pair of tunnels 4 km long. The chirp was caused by a change in the length of the tunnels by less than the width of a single proton. Seven milliseconds later, a similar detector in Washington detected a nearly identical chirp. Modelling of the signals revealed that the gravitational waves originated in a binary black hole system—a pair of black holes orbiting one another—located approximately 1.4 billion

gravitational waves Ripples in space-time.

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light years away. These black holes, each of about 30 solar masses, were orbiting so close to one another that they were generating immensely strong gravitational waves. The gravitational waves carried energy away from the system, causing the black holes to spiral in toward one another and ultimately merge. The gravitational waves detected at Earth were those emitted in the last moments before the two black holes collided. This event was spectacular confirmation not only of an old prediction of general relativity, but of the existence of black holes.

Black holes aren't the only sources of gravitational waves in the cosmos. On August 17, 2017, astronomers detected gravitational waves from the merger of a pair of neutron stars. Unlike black hole mergers, neutron star mergers produce copious visible light. Alerted by the gravitational waves, dozens of observatories witnessed this event, called GW170817. This type of event is known as a "kilonova" because it can be about 1000 times as bright as a classical nova. Kilonovae solve a long-standing problem concerning the origins of the heavier elements in the periodic table. Astronomers have long suspected that these elements formed during rapid nuclear reactions in extremely energetic environments, but were unable to pinpoint those environments. Kilonovae provide the solution: GW170817 alone is thought to have produced 10 Earth masses of gold and platinum, at least some of which were expelled into space before the remaining material collapsed to form a new black hole.

The **Big Picture**

The life and death stories of stars are important because Earth depends on one star, the Sun. Perhaps even more important, the lives and deaths of previous generations of stars created the chemical elements of which Earth and you are made. If those stars hadn't lived and died, you wouldn't exist. This chapter explored how the lives, deaths, and left-over remnants of stars depend on their masses. Stars with masses similar to that of the Sun end as white dwarfs, but more massive stars leave behind the strangest beasts in the cosmic zoo: neutron stars and black holes. Some matter from dying stars escapes back into the interstellar medium and is incorporated into new stars and the planets that form with them. The death of stars is part of a great cycle of stellar birth and death that includes the Sun, Earth, and you. By understanding the death of stars, you can better understand your role in the evolution of the universe.

Review and **Discussion Questions**

Review Questions

1. What happens to a star when it uses up the last of the hydrogen fuel in its core?
2. Why does helium fusion require a higher temperature than hydrogen fusion?
3. How will the Sun and stars smaller than the Sun die?
4. How can the contraction of an inert helium core trigger the ignition of a hydrogen-fusion shell?
5. Why does the expansion of a star's envelope make it cooler and more luminous?
6. How can star clusters confirm astronomers' theories of stellar evolution?
7. What causes an aging giant star to produce a planetary nebula?
8. Why can't a white dwarf have a mass greater than 1.4 solar masses?
9. How can a star of as much as 8 solar masses form a white dwarf when it dies?
10. What happens if an evolving star is in a binary star system?
11. How do massive stars die?
12. How can the inward collapse of the core of a massive star produce an outward explosion?
13. What is the difference between type I and type II supernovae?
14. What is the difference between a supernova explosion and a nova explosion?
15. What are neutron stars, and how do you know they really exist?
16. How are neutron stars and white dwarfs similar? How do they differ?
17. Why is there an upper limit to the mass of neutron stars?
18. If neutron stars are hot, why aren't they very luminous?
19. How does the lighthouse model explain pulsars?
20. What evidence can you cite that pulsars are neutron stars?
21. How can a neutron star in a binary system generate X-rays?
22. If nothing can escape a black hole, why can we detect black holes in X-rays?
23. How does the rate of passage of time differ between moving and stationary observers?

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24. What evidence do we have that black holes actually exist?
25. Discuss the possible causes of gamma-ray bursts.
26. If the Sun were replaced by a black hole of one solar mass, what would happen to Earth and the other planets of our solar system?
27. What astrophysical problem has been solved by the discovery of kilonovae?
28. **How Do We Know?** Why do scientists say that a hypothesis or theory is confirmed, but do not say it is proven?

Discussion Questions

1. False-colour radio images and time-exposure photographs of astronomical images show aspects of nature you can never see with unaided eyes. What other types of images do you know of that reveal phenomena invisible to your eye?
2. Elderly giant stars and newborn protostars both occupy similar positions in the H–R diagram. How can we be sure whether a given star is a giant or a protostar?
3. In your opinion, has the link between pulsars and neutron stars been sufficiently tested to be called a theory, or should it be called a hypothesis? What about the existence of black holes?
4. Why wouldn't an accretion disk orbiting a giant star get as hot as an accretion disk orbiting a compact object?
5. Is it possible that black holes don't exist at all, and we are being fooled by very dense neutron stars?

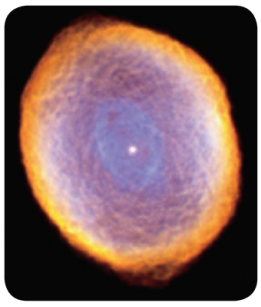
Learning to Look

1. The star cluster in this figure contains many hot, blue, luminous stars. Sketch its H–R diagram and discuss its probable age.



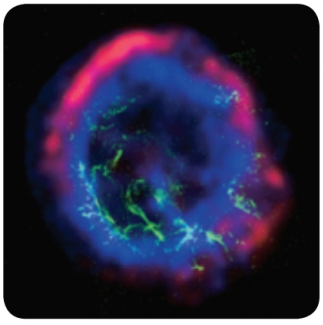
NASA/ESA/STScI/AURA/NSF/Hubble Heritage Team/The WFC3 Science Oversight Committee/R. O'Connell (Univ. of Virginia), F. Paresce (NIA), E. Young (USRA/SOFIA)

2. What processes caused a medium-mass star to produce the nebula as shown below? The nebula is now about 0.1 ly in diameter and still expanding. What will happen to it?



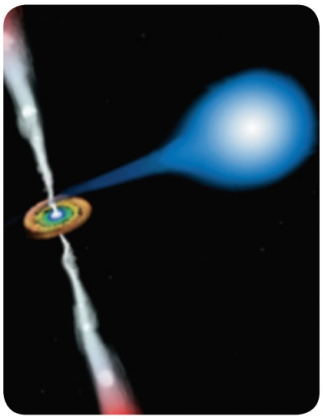
NASA/ESA/STScI/AURA/NSF/The Hubble Heritage Team/ R.Sahai(JPL -Caltech) and A. Hajan (NOAO)

3. The image as shown below combines X-ray (blue), visible (green), and radio (red) images. Observations show the sphere is expanding at a high speed and is filled with very hot gas. What kind of object produced this nebula? Roughly how old do you think it must be?



X-ray (NASA/CXC/SAO); Optical (NASA/HST); Radio (ACTA)

4. What is happening in the artist's impression as shown below? How would you distinguish between a neutron star and a black hole in such a system?



CKCM WEISS

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PART THREE

9 The Milky Way Galaxy



ESO/B. Tafreshi (twanight.org)

CHAPTER OUTLINE

9.1 The Discovery of the Galaxy
9.2 Spiral Arms and Star Formation
9.3 The Origin and History of the Milky Way
9.4 The Nucleus

GUIDEPOST

You have traced the life stories of stars from their birth in clouds of gas and dust to their deaths as white dwarfs, neutron stars, or black holes. Now you are ready to step back and view stars in vast communities called galaxies. This chapter focuses on our home galaxy, the Milky Way, and addresses several important questions:

- What is the evidence that we live in a galaxy?
- What is the evidence that our Milky Way is a spiral galaxy, and what are the spiral arms?
- What is the composition of the Milky Way Galaxy?
- How did the Milky Way Galaxy form and evolve?
- What lies at the centre of the Milky Way Galaxy?

Discovering the Milky Way Galaxy by answering these questions will bring you one more step toward understanding the universe as a whole. In the chapters that follow, you will leave your home galaxy and voyage out among the billions of other galaxies that fill the depths of the universe.

You live inside one of the largest of the star systems that fill the universe. Our Milky Way Galaxy is over 100 000 ly in diameter and contains over 100 billion stars. As you read this chapter, you will learn about not only your home galaxy but also how the stars of the galaxy have cooked up the atoms heavier than helium. You have already learned how the cores of massive stars make atoms heavier than helium and how supernovae blast those atoms back into space as well as other even heavier

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The Milky Way above the ALMA international radio telescope array, Atacama Desert, Chile

In less than a hundred years, we have found a new way to think of ourselves. From sitting at the center of the universe, we now find ourselves orbiting an average-sized sun, which is just one of millions of stars in our own Milky Way galaxy.

Stephen Hawking,
physicist and author

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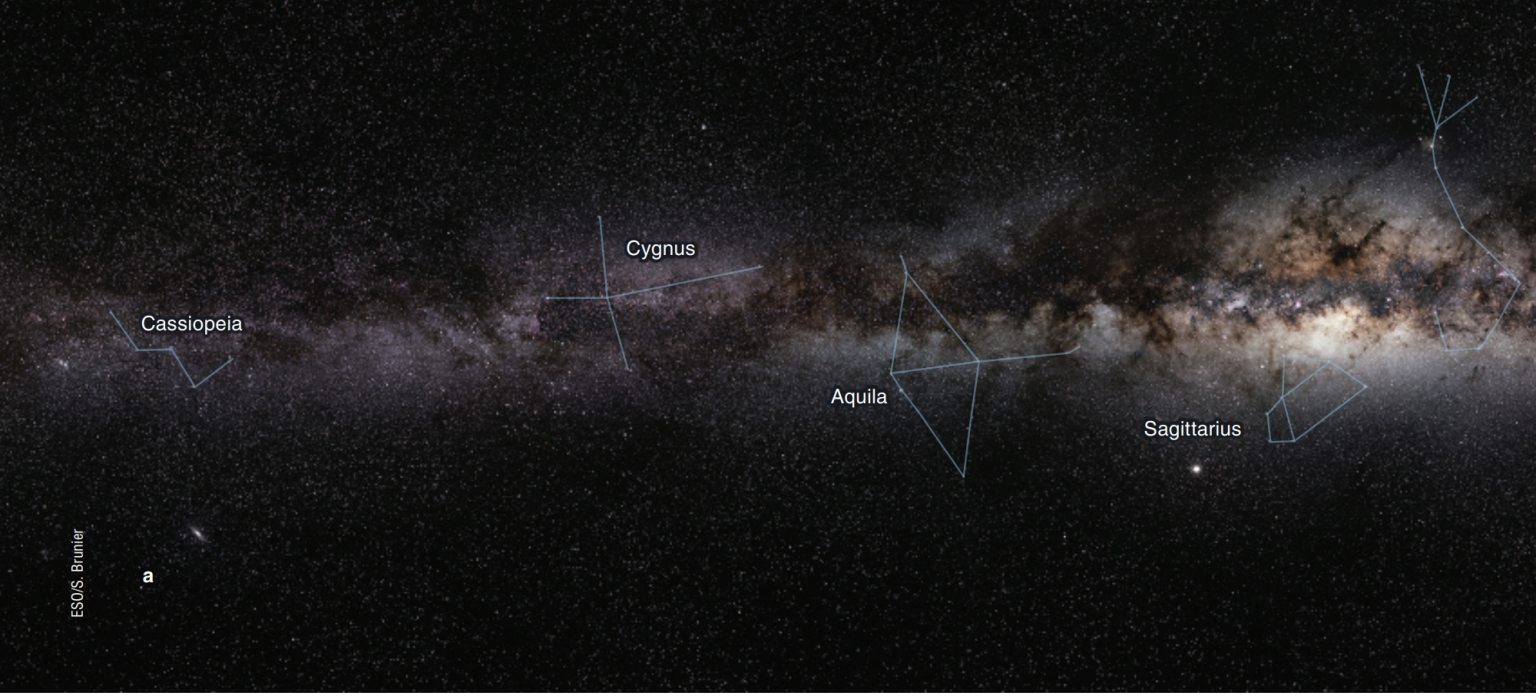


Figure 9.1 Milky Way all-sky panorama with constellations. The left half of (a) is seen from Earth's northern latitude, and the right half from the southern latitude. Galactic centre is in the constellation Sagittarius on the very right of (a), where the Milky Way is brightest. The left half of (b) is seen from Earth's southern hemisphere, and the right half from the northern latitudes.

atoms made during the supernova explosion. In this chapter you will see how the stars in the Milky Way Galaxy have, generation after generation, made the atoms now in your body.

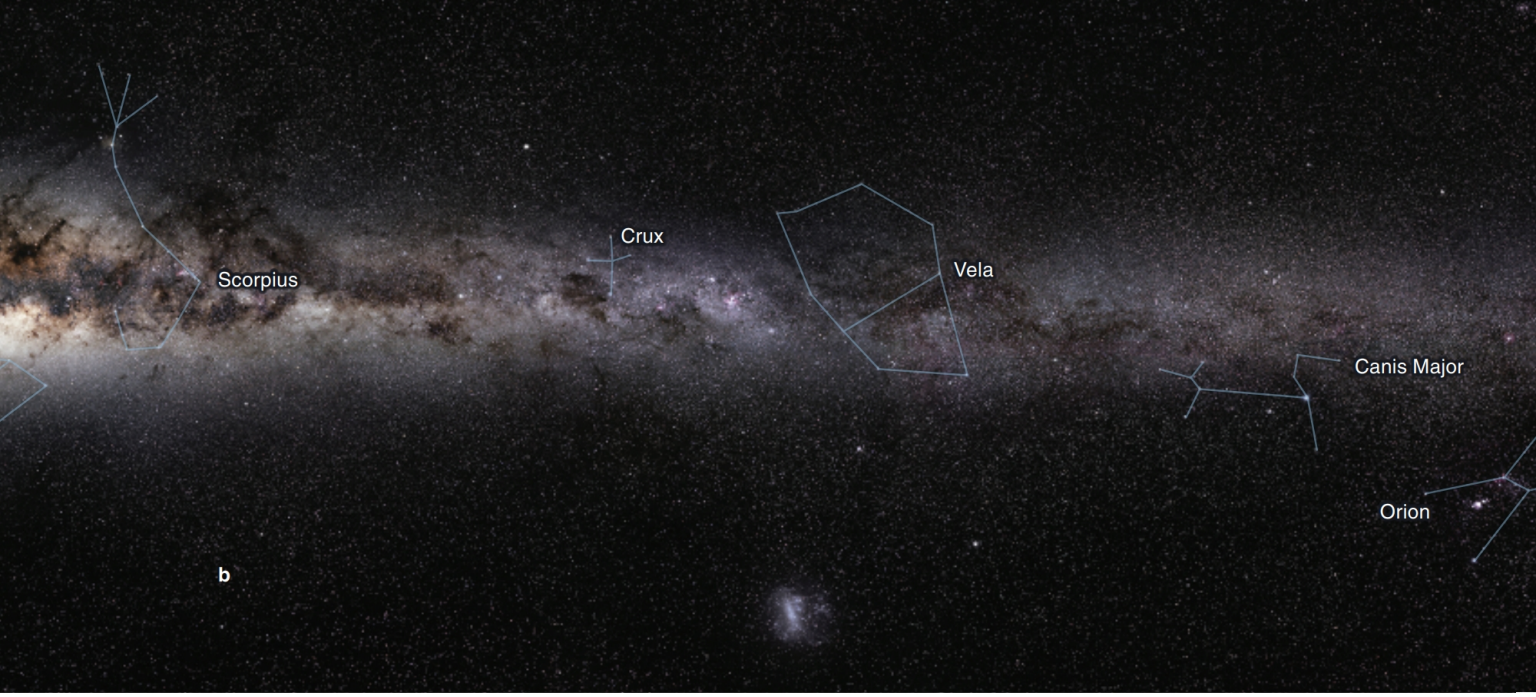
9.1 The Discovery of the Galaxy

It seems odd to say astronomers discovered something that is all around you. However, until the early 20th century, no one knew what the Milky Way was.

It isn't obvious that you live in a galaxy. You are inside and you see nearby stars scattered in all directions over the sky, whereas the more distant clouds of stars in the galaxy make a faint band of light circling the sky, as Figures 2.15 and 2.16 demonstrate. Figure 9.1 is a Milky Way panorama, which is composed from 51 wide-angle photographs taken all around the globe. Major constellations are labelled along the image. The Milky Way looks quite different for observers at various latitudes. In the northern hemisphere, it looks fainter and smoother than in the southern hemisphere (the brightest parts of the images). Many northern hemisphere cultures (Baltic, Finnish, Canadian Cree, for example) associated the Milky Way with "the path of the birds" migrating south. In Cree, the Milky Way is *Neepin Pinesisuk Mesinaw*, "the summer birds' path," with Niska, the celestial goose that terrestrial birds followed when migrating (known also as Cygnus, the "swan" constellation) visible in the centre of Figure 9.1 (a) as the large cross. To the Vikings, the Milky way was a road to the gods ("Road to Valhalla"); and to the Maya, it was the way to the underworld. Going south, the Milky Way becomes richer: dark nebulae appear, breaking the structure into branches, like river systems. Chinese, Japanese, Korean, Hindu, Australian (Yolngu), and Peruvian lore regarded it as the celestial counterpart of terrestrial rivers. To the Quechua of Peru, the Vilcanota River was a terrestrial reflection of a heavenly river, and the two rivers were exchanging water in a unique water system. The !Kung people from the Kalahari in Botswana and Chumash from California saw the Milky Way straight overhead and considered it "the backbone of night."

The origin of the name Milky Way comes from ancient Greeks. They named it *galaxias kuklos*, the "milky circle." The Romans changed the name to *via lactea*, "milky road" or "milky way." It was not until early in the 20th century that astronomers understood that humans live inside a great wheel of stars and that the universe is filled with other such star systems. Drawing on the Greek word for milk, astronomers called these star systems *galaxies*.

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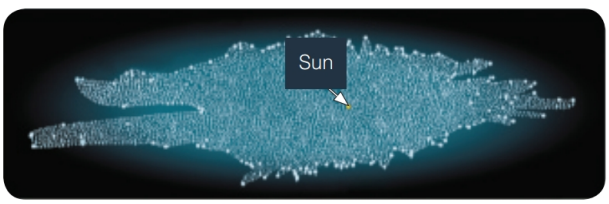
The Great Star System

Centuries before Galileo's definitive observational proof in 1610, philosophers and astronomers worldwide proposed that the Milky Way was a band of starlight. Greek philosophers Anaxagoras and Democritus, around 400 bce, argued that the Milky Way consisted of myriad distant stars. The same description is found in the writings of Latin poet Manilius (1st century CE), Persian astronomer Abū Rayhān al-Bīrūnī (11th century), Andalusian astronomer Avempace (12th century), and famous Suni philosopher Ibn Qayyim Al-Jawziyya (14th century).

Galileo's telescope revealed that the glowing Milky Way is made up of stars, and later astronomers realized that the great cloud of stars in which the Sun is located, a star system, must be wheel shaped. If it were spherical, for example, you would see stars scattered more or less uniformly in all directions over the sky. Only a wheel or disk shape would look, from the inside, like the Milky Way band encircling the sky.

In the 18th century, English astronomers Sir William Herschel and his sister Caroline attempted to gauge the true shape of the star system by counting stars in 683 different directions in the sky. In directions where they saw more stars, they assumed the star system extended further into space. They concluded that the star system had a disk shape with some noticeable "holes" where stars were lacking around the edges (see Figure 9.2). Modern astronomers know that those apparent holes are caused by dense clouds of gas and dust that block the view of more distant stars. The Herschels counted similar numbers of stars in most directions around the Milky Way and concluded that the Sun and Earth were near the centre of the star system.

As the 20th century began, astronomers still believed that the Sun was located near the centre of a wheel-shaped star system that they estimated was about 15 000 ly in diameter. Further quest to understand the size of the galaxy, Earth's location in it, and the galaxy's location in a much larger universe of other galaxies is an adventure that begins with a woman studying stars that pulsate



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Figure 9.2 In 1785, William Herschel published this diagram showing the shape of the star system as if it could be viewed edge-on from outside.

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Cepheid variable stars Variable stars with pulsation periods of 1 to 60 days and whose period of variation is related to their luminosity.

instability strip The region of the H–R diagram in which stars are unstable to pulsation. A star evolving through this strip becomes a variable star.

and leads to a man studying distant star clusters. The next section follows that story because it is an important moment in human history and because it illustrates how scientists build on the work of their predecessors; step-by-step they refine their ideas about the natural world.

The Size of the Milky Way

Stars change from one stage to another over time scales unimaginable for humans. It seems like they are eternal and unchanging, but astronomers have known for centuries that some stars change in brightness. Novae and supernovae burst into view, grow brighter, and then fade, but many other variable stars actually pulsate like beating hearts. The period of pulsation is the time it takes a star to complete a cycle from bright to faint to bright again. You will learn next how the properties of some types of variable stars allowed astronomers to measure the size of the galaxy.

In 1912, Henrietta Leavitt (1868–1921) was studying a star cloud (that we now know to be a galaxy) in the southern sky known as the Small Magellanic Cloud. On her photographic plates she found many variable stars, and she noticed that the brightest had the longest periods. Because all the variables were in the same cloud at nearly the same distance, she concluded that there was a relationship between the pulsation periods and intrinsic brightness—that is, the luminosity or true total power output—of those variable stars.

The stars Leavitt saw, **Cepheid variable stars**, are named after the first such star discovered, Delta Cephei. They are giant and supergiant stars with pulsation periods of 1 to 60 days and with properties that lie in a region of the H–R diagram known as the **instability strip** (Figure 9.3). As a star uses up its hydrogen fuel, its main-sequence life of hydrostatic equilibrium ends, and the balance between the force of gravity and interior pressure is lost. As gravity takes over, the star shrinks, the density of the gas increases, and the gas becomes hotter. The pressure in the gas makes it expand outward, so the star looks larger and brighter. As the density gets lower, the energy flows through more transparent gas that now cools, and gravitational force is overwhelming, causing the star to shrink. This pulsating continues, and in each stage of a cycle some energy is lost, which slows down this process over time. At last, the star stops pulsating, and we can say that

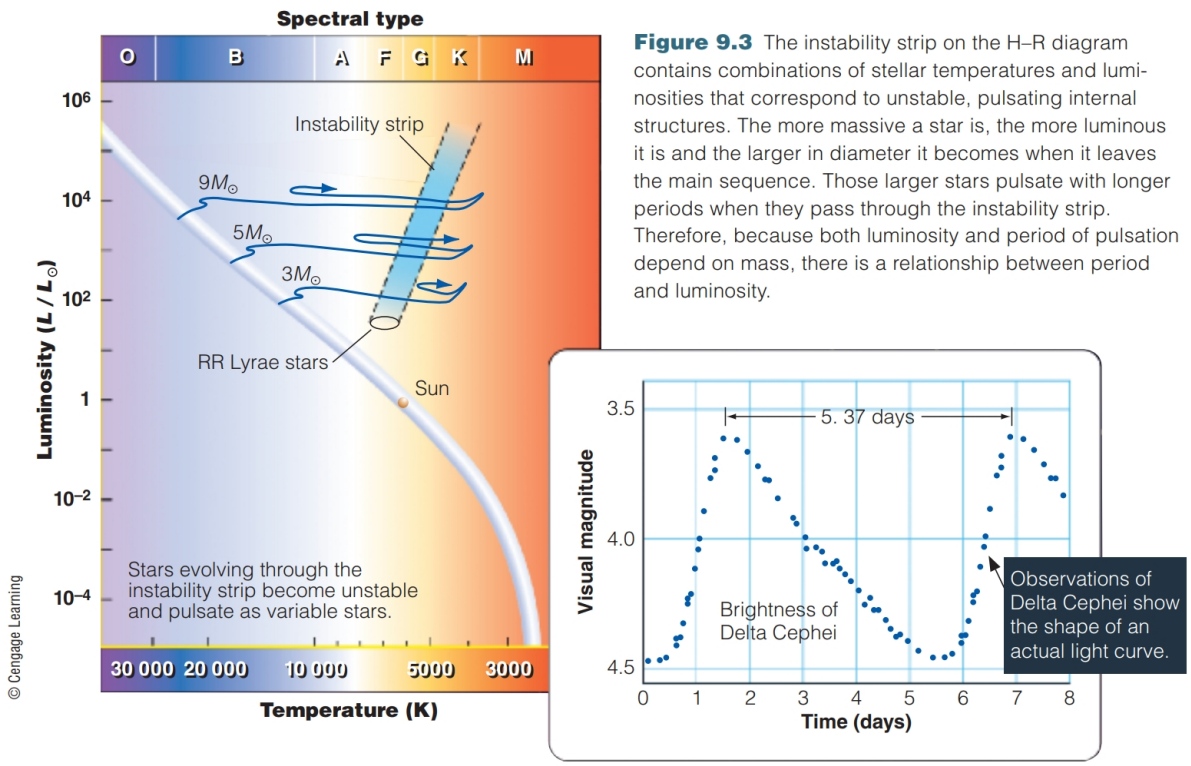
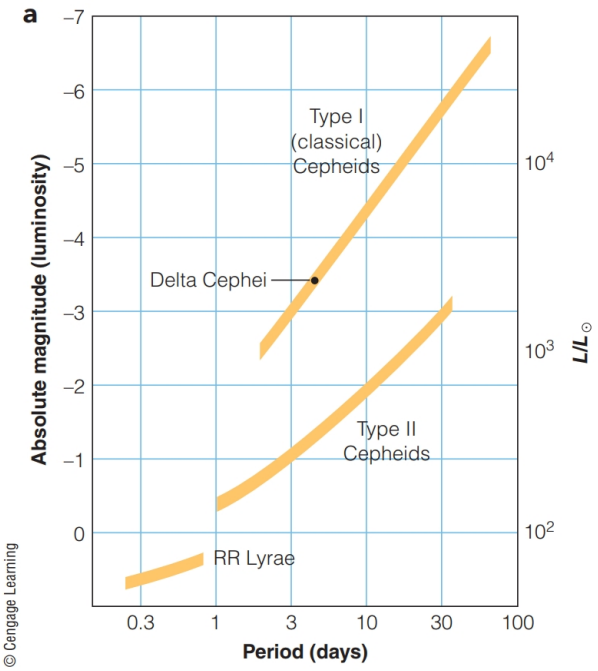


Figure 9.3 The instability strip on the H–R diagram contains combinations of stellar temperatures and luminosities that correspond to unstable, pulsating internal structures. The more massive a star is, the more luminous it is and the larger in diameter it becomes when it leaves the main sequence. Those larger stars pulsate with longer periods when they pass through the instability strip. Therefore, because both luminosity and period of pulsation depend on mass, there is a relationship between period and luminosity.

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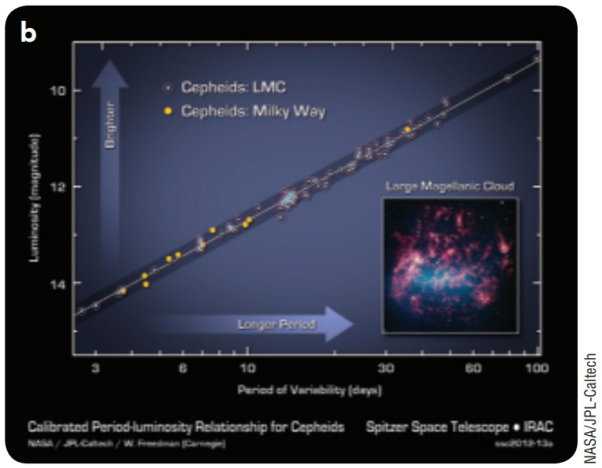


Figure 9.4 (a) The period–luminosity diagram is a graph of the luminosity of variable stars versus their periods of pulsation. The diagram is used for distance calculations in which we compare apparent and absolute magnitudes. For that reason, it is most convenient to represent luminosity on the vertical axis with absolute magnitude. Today, astronomers know there are two types of Cepheids as well as other similar types of variable stars. This is something astronomers in the early 20th century could not recognize in their limited data, which caused some errors in the first determinations of the size of the Milky Way. (b) Cepheid variable stars are so luminous that they can be seen in other galaxies. This graph illustrates the Cepheid period–luminosity relationship from the Milky Way and the nearby galaxy Large Magellanic Cloud (LMC) shown in the insert. The data shown are from NASA's Spitzer Space Telescope, which has made the most precise measurements yet.

it "left the instability strip." Massive stars pulsate more slowly. Lower-mass, less luminous stars pulsate faster. Leavitt noticed that the long-period Cepheids are more luminous than the short-period Cepheids. This is now known as the **period–luminosity relation**, shown graphically in Figure 9.4. You may be interested to learn that the North Star, Polaris, is a Cepheid variable with a pulsation period of about 4 days; however, recent observations show a gradual slowing down, which means that the North Star is slowly evolving off the instability strip.

Star Clusters and the Centre of the Galaxy

Early in the 20th century, American astronomer Harlow Shapley (1885–1972) noticed that different kinds of star clusters had different distributions in the sky. In Chapter 8 you learned about two types of star clusters: open clusters and globular clusters. Open clusters are concentrated along the Milky Way. Globular clusters are widely scattered, but Shapley noticed that they were more common toward the constellations Sagittarius and Scorpius (see Figure 9.5a).

Shapley assumed that the concentration of globular clusters is controlled by the combined gravitational field of all the stars in the galaxy. In that case, he realized he could study the size and extent of the galaxy by studying the globular clusters. To do that he needed to measure the distances to as many globular clusters as possible.

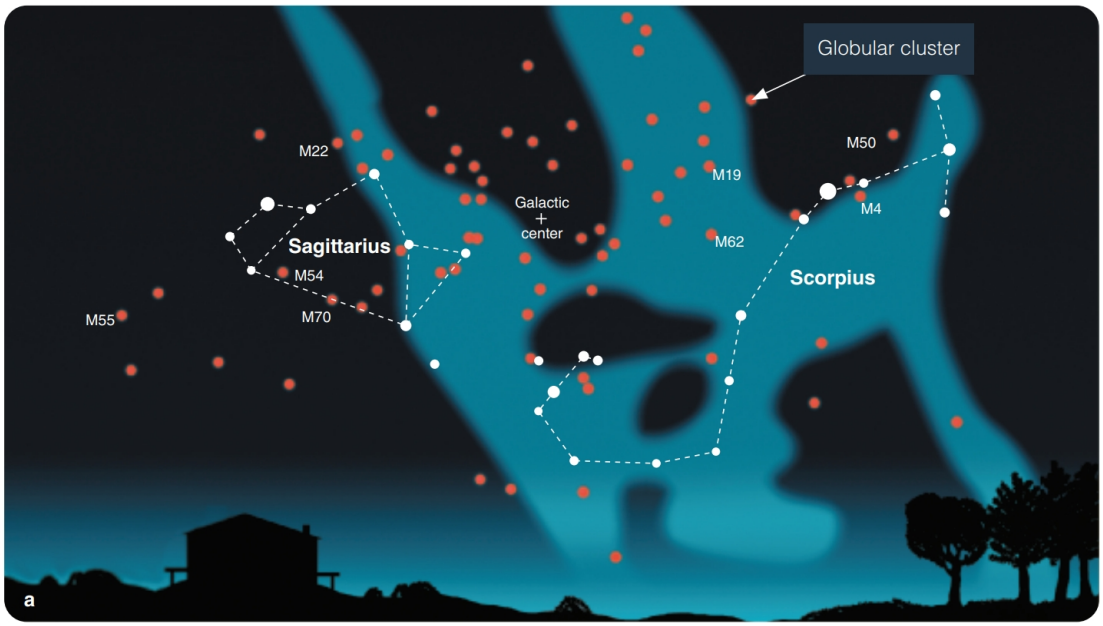
Globular clusters are much too far away to have measurable parallaxes, but they do contain variable stars. Shapley knew of Leavitt's work on these stars, which depended on their relative, rather than true, luminosities. Cepheids are rare, and there are none near enough to have measurable parallaxes, so their true luminosities were not then known. Shapley realized that he could calculate the distance to the globular clusters if he found the true luminosities of the Cepheid variable stars in the clusters.

Through a statistical process involving measurements of position shifts due to their motions along the celestial sphere, called **proper motions**, Shapley found the average distances of a few of the nearest Cepheids, and from that their average luminosities. That meant he could

period–luminosity relation The relation between period of pulsation and intrinsic brightness among Cepheid variable stars.

proper motion The rate at which a star moves across the sky, measured in arc seconds per year.

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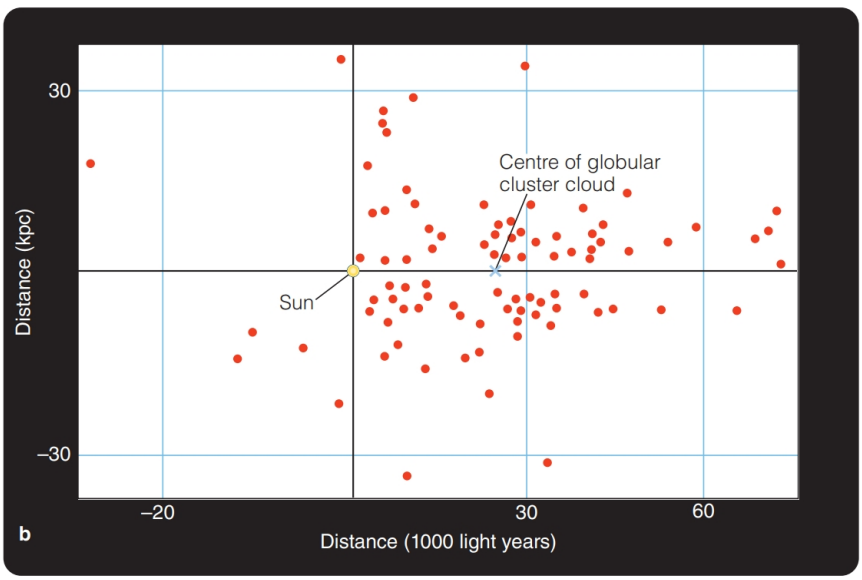


Figure 9.5 (a) Nearly half of the catalogued globular clusters (red dots) are located in or near Sagittarius and Scorpius. A few of the brighter globular clusters (labelled with their catalogue designations) are visible with binoculars or small telescopes. Constellations are shown as they appear above the southern horizon on a summer night as seen from mid-latitudes in the northern hemisphere. (b) This is a "side view" of the Milky Way Galaxy's globular clusters. Shapley's study of the clusters and their distances shows that the globular clusters were not centred on the Sun, which is located at the origin of this graph, but rather they form a great cloud centred far away in the direction of Sagittarius. Distances are given in thousands of light-years. Shapley's original calibration produced values more than two times larger than the modern calibration.

replace Leavitt's apparent magnitudes with absolute magnitudes on the period–luminosity diagram (Figure 9.4). Astronomers say that Shapley **calibrated** the variable stars for distance (see **How Do We Know? 9.1**).

calibrate To make observations of reference objects, checks on instrument performance, calculations of unit conversions, and so on, needed to completely understand measurements of unknown quantities.

Having calibrated the Cepheids, Shapley could find the distance to the globular star clusters. He identified the variable stars in the clusters and determined their apparent magnitudes from his photographs. Comparison of apparent and absolute magnitudes gave him the distance to the star cluster based on the inverse square law for light (see Chapter 6). Another type of variable stars, less massive than Cepheids but much more common in numbers, the RR Lyrae—named after the first discovered such variable star, RR in the Lyra constellation—also have a characteristic pulsation and known period–luminosity relationship (Figure 9.4a). Shapley found numerous RR Lyrae stars in globular clusters and was able to calculate distances to clusters.

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HOW DO WE KNOW? 9.1

The Calibration of One Parameter to Find Another

Astronomers often say that Shapley "calibrated" the Cepheids for the determination of distance, meaning that he did all the detailed background work so that the Cepheids could be used to find distances. Other astronomers could then use the Cepheids without repeating the calibration.

Calibration is actually very common in science. Chemists, for instance, have carefully calibrated the colours of certain compounds against acidity. They can quickly measure the acidity of a solution by dipping in a slip of paper containing the indicator compound and looking at the colour. They don't have to repeat the careful calibration of the paper slips every time they measure acidity.

Engineers in steel mills have calibrated the colour of molten steel against its temperature. They can use a handheld device that measures the colour of the blackbody radiation from a ladle of molten steel and then looks up the temperature from a calibrated table. They don't have to repeat the calibration every time. Astronomers have made the same kind of colour–temperature calibration for stars.

As you read about any science, notice how calibrations are used to simplify common measurements. But notice, too, how important it is to get the calibration right. An error in calibration can throw off every measurement made with that calibration. Some of the biggest errors in science have been errors of calibration.

Finally, Shapley plotted the direction and distance to the globular clusters and saw that they formed a great swarm that was not centred on the Sun. Instead, the centre of the galaxy's cloud of clusters lay many thousands of light-years in the direction of Sagittarius. By analogy, if you see a bunch of tall buildings, and they are all together in one direction away from you, you might conclude that downtown is over there, and you are in the suburbs. Evidently the centre of the star system is in Sagittarius and far away. The star system is much bigger than anyone had suspected (Figure 9.5b). You live not near the centre of a small star system but in the suburbs of a very big wheel of stars—a galaxy.

Why did astronomers before Shapley think we lived near the centre of a small star system? The answer: Space is filled with gas and dust that dims the view of distant stars. When you look toward the band of the Milky Way, you can see only the neighbourhood near the Sun. Most of the star system is hidden, and like a traveller in a fog you seem to be at the centre of a small region. Shapley was able to see the globular clusters at greater distances because they lie outside the plane of the Milky Way and are not dimmed very much by the interstellar dust.

Building on Shapley's work, other astronomers began to suspect that some of the faint patches of light visible through telescopes were other galaxies like our own. In 1923, Edwin Hubble photographed individual stars in the Andromeda Galaxy, and in 1924, he identified Cepheids there, allowing its distance to be estimated. As a result, it became clear that our galaxy is just one in a universe filled with galaxies. You will see in two following chapters consequences of Hubble's discoveries for our understanding of place in the universe.

Components of the Galaxy

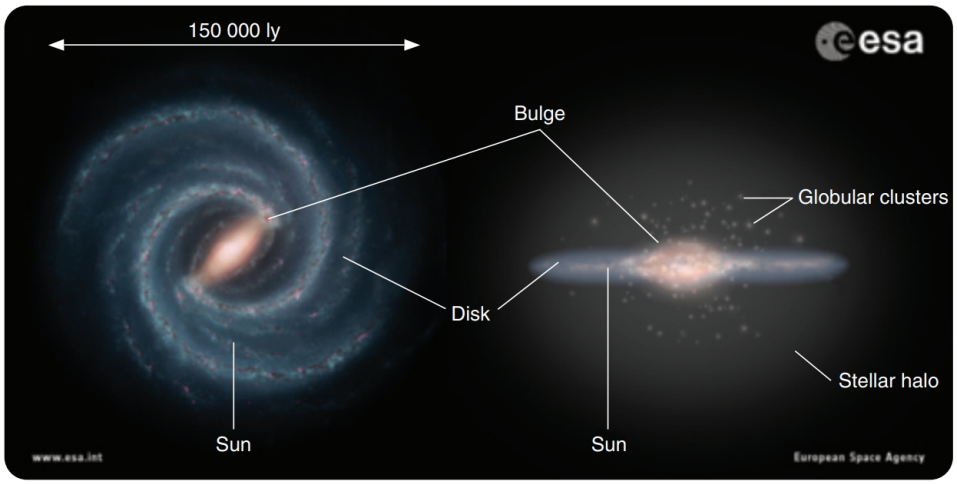
Our galaxy, like many others, contains two primary components: a disk and a sphere. Figure 9.6 shows these components and other features discussed in this section.

The **disk component** consists of all matter confined to the plane of rotation—stars, open star clusters, and nearly all of the galaxy's gas and dust. As you will learn in more detail in the next section, the disk is the site of most of the star formation in the galaxy because it contains a lot of gas. Consequently, the disk is illuminated by recently formed brilliant, blue, massive stars and has an overall relatively blue colour.

The diameter of the disk and the position of the Sun are difficult to determine accurately. Interstellar dust blocks the view in the plane of the galaxy, so astronomers cannot see to the centre or to the edge easily, and the outer edge of the disk is not well defined. Most recent studies suggest the Sun is about 26 000 ly from the centre. The Sun and Earth seem to be about two-thirds of the way from the centre to the edge, so the diameter of our galaxy appears to be about 100 000 ly; however, most recent data from international large surveys of stars in the Milky Way galaxy

disk component All material confined to the plane of the galaxy.

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NASA/JPL-Caltech; right: ESA; layout: ESA/ATG medialab, CC BY-SA 3.0 IGO (adapted)

Figure 9.6 An artist's conception of the Milky Way Galaxy: seen face-on and edge-on. Note the position of the Sun in the disk and the distribution of globular clusters in the halo. Hot, blue stars light up the spiral arms of the disk which is filled with gas and dust. Only the inner halo is shown here. At this scale, the entire halo would be larger than a dinner plate. Also note that globular clusters are not to scale in this figure.

indicate the size of the disk could be even two times larger. This is the diameter of the luminous part of our galaxy, the part you would see from a distance. You will learn later that strong evidence shows our galaxy is much larger than that, but the outer parts are not luminous. It may surprise you to learn that the disk of spiral galaxies is very thin; in fact, the disk of the Milky Way is merely 300 ly.

Observations made at other than visual wavelengths can help astronomers peer through the dust and gas. Infrared and radio photons have wavelengths long enough to be unaffected by the dust. Thus, a map of the sky at long infrared wavelengths (i.e., far-infrared) reveals the disk of our galaxy (Figure 4.18b).

The most striking features of the disk component are the **spiral arms**—long curves of bright stars, star clusters, gas, and dust. Such spiral arms are easily visible in other galaxies, and you will see later how astronomers found that our own galaxy has a spiral pattern.

spiral arms Long spiral pattern of bright stars, star clusters, gas, and dust. Spiral arms extend from the centre to the edge of the disk of spiral galaxies.

spherical component The part of the galaxy that includes all matter in a spherical distribution around its centre (the halo and central bulge).

halo The spherical region of a spiral galaxy, containing a thin scattering of stars, star clusters, and small amounts of gas.

central bulge The dense cloud of stars that surrounds the centre of our galaxy.

The second component of our galaxy is the **spherical component**, which includes all matter in our galaxy scattered in a roughly spherical distribution around the centre. This includes a large halo and the central bulge.

The **halo** is a spherical cloud of thinly scattered stars and globular star clusters. It contains only about 2 percent as many stars as the disk of the galaxy and has very little gas and dust. Consequently, with no raw material available, no new stars are forming in the halo. In fact, the halo stars are mostly old, cool giants or dim lower-main-sequence stars—plus, as revealed by recent careful studies, old white dwarfs that are difficult to detect. Astronomers can map the halo of our galaxy by studying the more easily detected giant stars.

The **central bulge** is the dense cloud of stars that surrounds the centre of our galaxy. It has a radius of about 6500 ly and is a slightly flattened spheroid. It is hard to observe because thick dust in the disk scatters and absorbs radiation of visible wavelengths, but observations at longer wavelengths can penetrate the dust. The bulge seems to contain little gas and dust, and there is not much star formation there. Most of the stars in the central bulge are old, cool stars like those in the halo.

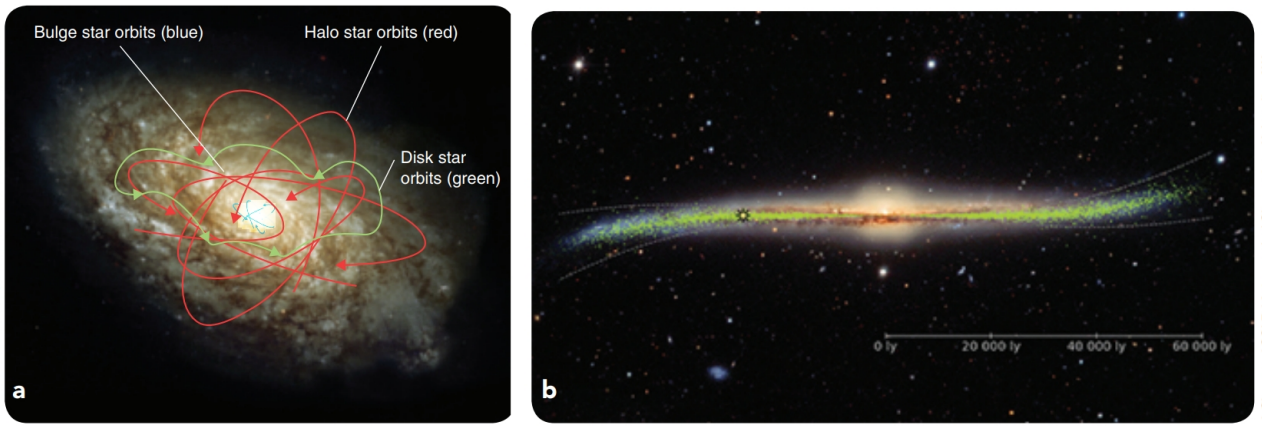
The Mass of the Galaxy and the Dark Matter

The vast numbers of stars in the disk, halo, and central bulge lead to a basic question: How massive is the galaxy?

When you needed to find the masses of stars, you studied the orbital motions of the pairs of stars in binary systems. To find the mass of the galaxy, you must look at the orbital motions of the stars within the galaxy. Every star in the galaxy follows an orbit around the centre of mass of the galaxy. In the disk, the stars follow concentric circular orbits, and astronomers say the disk of the galaxy rotates. That rotation can allow an estimate of the mass of the galaxy. Consequently, any discussion of the mass of the galaxy is also a discussion of the rotation of the galaxy and the orbits of the stars within the galaxy.

Astronomers can find the orbits of stars by finding how they move. The Doppler effect reveals a star's radial

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J. Skowron / OGLE / Astronomical Observatory, University of Warsaw, based on Skowron et al. 2019, Science, 365, 6452, 478

Figure 9.7 (a) Shown here is a spiral galaxy NGC 4144, at a distance of about 60 million light-years from Earth, in the constellation of Coma Berenices. Stars in the galactic disk have nearly circular orbits that curve in and out of the plane of the galaxy, but follow the plane. Stars in the halo have randomly oriented, highly eccentric elongated orbits around the centre of the galaxy. (b) This artist's illustrations shows our galaxy's warped disk, traced out by young variable stars called Cepheids (green points).

velocity (see Chapter 5). In addition, if astronomers can measure the star's proper motion, they can find the velocity of the star perpendicular to the radial direction. Combining all of this information with estimated distance to the star, astronomers can find the shape of the star's orbit.

You can see in Figure 9.7 that the orbital motions of the stars in the halo are strikingly different from those in the disk. In the halo, each star and globular cluster follows its own randomly tipped elliptical orbit. (To review globular clusters, see **Visualizing Astronomy 8.1, Star Cluster H–R Diagrams**.) These orbits carry the stars and clusters far out into the spherical halo, where they move slowly, but when they fall back into the inner part of the galaxy their velocities increase. Motions in the halo do not resemble a general rotation but are more like the random motions of a swarm of bees. In contrast, the stars in the disk of the galaxy move in the same direction in nearly circular orbits that lie in the plane of the galaxy. The Sun is a disk star and follows a nearly circular orbit around the galaxy that always remains within the disk. The most recent surveys of distribution of gas, dust and stars have revealed that the Milky Way's disk warped, Figure 9.7b.

CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Royal Astronomical Society/Science Source

The Dominion Astrophysical Observatory (DAO) in Victoria, British Columbia

John Stanley Plaskett

John S. Plaskett, originally from Hickson, Ontario, worked as a mechanic in the physics department at the University of Toronto. At the age of 30 he decided to enter undergraduate studies. After graduating in 1899, he was hired at Ottawa's Dominion Observatory—first as a mechanic, then as an astronomer. Plaskett made great contributions to astronomy in many areas. He discovered a massive binary star, named after him as Plaskett's Star. His work on the radial velocities of galactic stars confirmed Oort's model of galactic rotation. In 1935, he published the first detailed analysis of the structure of the Milky Way Galaxy. Interested in engineering and astronomy, he improved the Dominion Observatory telescope, building a spectroscope for it. He lobbied the Canadian parliament for a 1.8-m telescope that was, under his supervision, built for the Dominion Astrophysical Observatory in Victoria, BC. When completed in 1918, this was the world's largest telescope. Still working, it is named the Plaskett Telescope. He was the director of the Dominion Astrophysical Observatory until 1935. In 1984, Minor Planet No 2905 was named Plaskett in honour of J. S. Plaskett and his son H. H. Plaskett, also an astronomer. The Royal Astronomical Society of Canada and the Canadian Astronomical Society have established the Plaskett Medal, which is awarded to the top graduate from a Canadian university who is judged to have submitted the most outstanding doctoral thesis in astronomy and astrophysics.

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You can use the orbital motion of the Sun to find the mass of the galaxy inside the Sun's orbit. The Sun moves at about 240 km/s in the direction of Cygnus, carrying Earth and the other planets of our solar system along with it. Because its orbit is a circle with a radius of 26 000 ly, you can divide the circumference of the orbit by the velocity and find that the Sun completes a single orbit in about 210 million years.

If you think of the Sun and the centre of mass of our galaxy as two objects orbiting each other, you now have enough information to determine the mass of the galaxy. The Milky Way Galaxy must have a mass of about 100 billion solar masses. This estimate is uncertain for a number of reasons. First, you don't know the radius of the Sun's orbit with great certainty. Astronomers estimate the radius as 26 000 ly, but they could be wrong by 10 percent or more, and the radius gets cubed in the calculation, which has a large effect. Second, this estimate of the mass includes only the mass inside the Sun's orbit. A uniform spread of mass outside the Sun's orbit will not affect its orbital motion. Thus, 100 billion solar masses is a lower limit for the mass of the galaxy. However, no one knows exactly how much to increase the estimate to include the rest of the mass in the galaxy that lies outside the Sun's orbit.

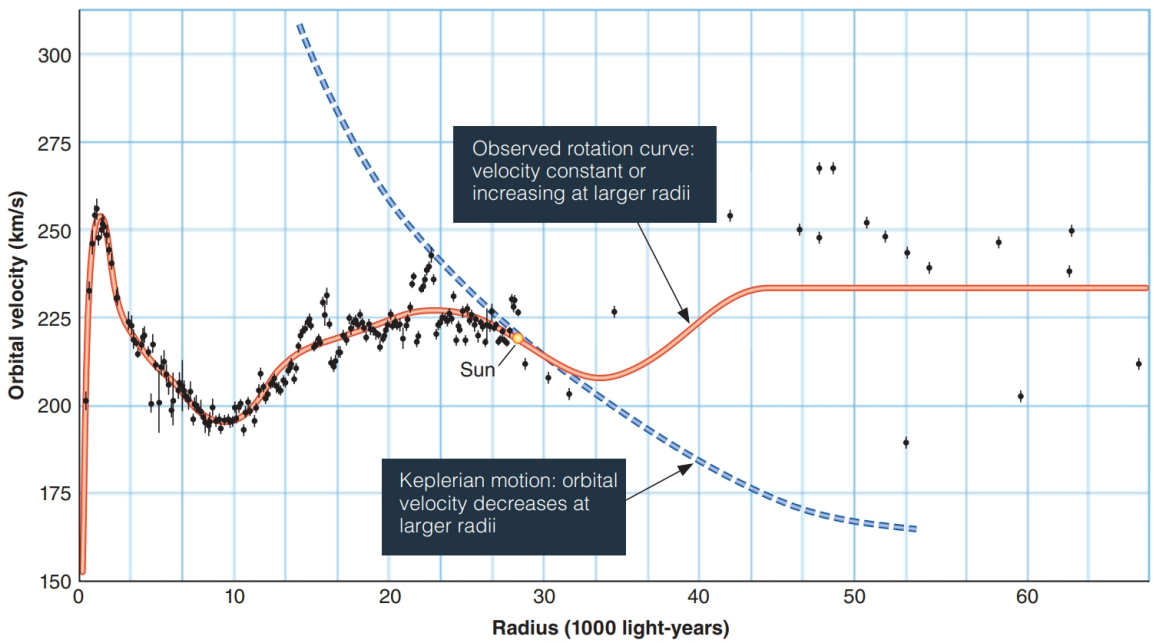
rotation curve A graph of orbital velocity versus radius in the disk of a galaxy.

dark halo The low-density extension of the halo of our galaxy, believed to be composed of dark matter.

The measured motion of the stars shows that the disk does not rotate as a solid body. Each star follows its own orbit, and stars in some regions have shorter or longer orbital periods than the Sun. This is called differential rotation. (Recall from Chapter 5 the term *differential rotation* as it applied to the Sun.) The graph in Figure 9.8 provides an example of the orbital velocity of stars at various orbital radii in the galaxy; the graph is called a **rotation curve**. If all of the mass in the galaxy were concentrated at its centre, the orbital velocity would be high near the centre and decline away from the centre. This kind of motion has been called *Keplerian motion* because it follows Kepler's third law, and it applies to our solar system, where nearly all the mass is in the Sun.

You already know the galaxy's mass is not all concentrated at its centre, but if most of the mass were inside the orbit of the Sun, the orbital velocities should decline at greater distances. Many observations confirm, however, that velocities do not decline and may actually increase at greater distance; this observation shows that larger and larger orbits enclose more and more mass. Although it is difficult to determine a precise edge to the visible galaxy, it seems clear that large amounts of matter are located beyond what seems to be the limit of the galaxy's luminous matter.

The evidence is clear that extra mass lies in an extended halo sometimes called a **dark halo**. It may



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Figure 9.8 The rotation curve of our galaxy is plotted here as orbital speed versus radius. Data points show measurements made by radio telescopes. Observations outside the orbit of the Sun are much more uncertain, and the data points scatter widely. Orbital speeds do not decline outside the orbit of the Sun, as you would expect if most of the mass of the galaxy were concentrated toward the centre. Rather, the curve is approximately flat at great distances, suggesting that the galaxy contains significant mass outside the orbit of the Sun.

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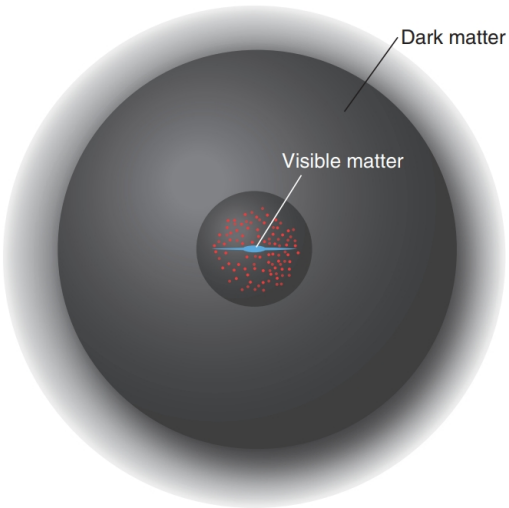


Figure 9.9 The rotation curve of spiral galaxies shows that only 10 percent of mass is in the form of visible (regular) matter. Ninety percent is something invisible and does not interact, or only very weakly interacts, with regular matter; it is called the *dark matter*. Visible matter seems to be embedded in a massive halo of dark matter.

extend up to 10 times farther than the edge of the visible disk and could contain 10 times more dark matter than visible (regular) matter in our galaxy (see Figure 9.9). This is the case with all spiral galaxies. Unlike luminous matter, which shows its existence by emitting electromagnetic radiation, this form of matter is not producing any light. Astronomers call it **dark matter**, which in fact means invisible, and conclude that it must be some as yet unknown form of matter.

Dark matter is difficult to detect, and it is even harder to explain. Some astronomers have suggested that dark matter consists of low-luminosity white dwarfs, brown dwarfs, and black holes scattered through the halos of galaxies. These objects were called MACHOS (massive compact halo objects). Searches for MACHOS in the halo of our galaxy haven't found enough to make up most of the dark matter. Astronomers are forced to conclude that the dark matter is made up of unexpected forms of matter. Until recently neutrinos were thought to be massless, but studies now suggest they have a very small mass. Thus, they can be part of the dark matter, but their masses are too low to make up all of the dark matter. There must be some other undiscovered form of matter in the universe that is detectable only by its gravitational field. Included among the most likely candidates are WIMPs (weakly interacting massive particles). These hypothetical subatomic particles are not made up of ordinary matter, otherwise we would be able to detect them in some electromagnetic wave range. They are weakly interacting, so they can pass through ordinary matter without any effects. They have a mass and must interact with visible matter gravitationally.

The problem becomes even more obvious in clusters of galaxies, as you will see in following chapters that will return to dark matter, one of the fundamental unresolved problems of modern astronomy.

9.2 Spiral Arms and Star Formation

The most striking feature of galaxies like the Milky Way is the system of spiral arms that wind outward through the disk and contain swarms of hot, blue stars; clouds of dust and gas; and young star clusters. These young objects hint that the spiral arms involve star formation. As you try to understand the spiral arms, you face two questions. First, how can you be sure our galaxy has spiral arms when Earth is embedded inside the galaxy and your view is obscured by gas and dust? Second, why doesn't the differential rotation of the galaxy destroy the arms? The answers to both questions involve star formation.

Tracing the Spiral Arms

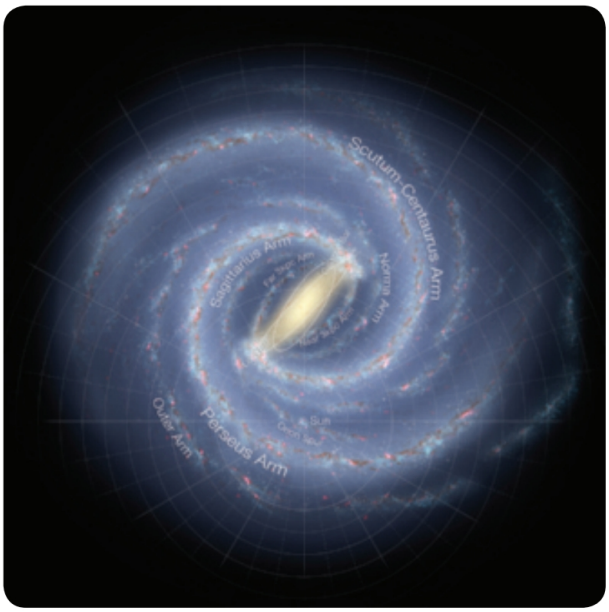
Studies of other galaxies show that the spiral arms contain hot, blue stars, and so one way to study the spiral arms of our own galaxy is to locate these stars. Fortunately, this is not difficult, since O and B stars are often found in associations and are easy to detect across great distances because they are very luminous. Unfortunately, at these great distances their parallax is too small to measure, so their distances must be found by other means, usually by spectroscopic parallax (see Chapter 6).

O and B associations in the sky are not located randomly; rather they outline three spiral arms near the Sun, which have been named for the prominent constellations through which they pass (Figure 9.10). Objects used to map spiral arms are called **spiral tracers**. O and B associations are good spiral tracers because they are bright and easy to see at great distances. Other

dark matter Nonluminous matter that is detected only by its gravitational influence.

spiral tracer Object used to map the spiral arms—for example, O and B associations, open clusters, clouds of ionized hydrogen, and some types of variable stars.

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NASA/JPL-Caltech/ESO/R. Hurt

Figure 9.10 This detailed annotated artist's impression shows the structure of the Milky Way. Within the Milky Way Galaxy gas and dust block your view of most of the galaxy's disk, but near the Sun young O and B stars fall along bands that appear to be segments of spiral arms. The shape of the central bulge is elongated into a bar.

tracers include young open clusters, clouds of hydrogen ionized by hot stars (emission nebulae), and certain higher-mass variable stars.

Notice that all spiral tracers are young objects. O stars, for example, live for only a few million years. If their orbital velocity is about 200 km/s, they cannot have moved more than about 1600 ly since they formed. This is less than the width of a spiral arm. Because they don't live long enough to move away from the spiral arms, they must have formed there. The youth of spiral tracers provides an important clue about spiral arms. Somehow they are associated with star formation.

Radio telescopes can detect emission from clouds of cool, neutral hydrogen gas. In 1995, the Canadian Galactic Plane Survey started mapping gas and dust in the galactic disk. This project initiated a wide international collaboration. To date, large radio telescopes around the globe cover almost 90 percent of our Milky Way's gaseous dusty disk, revealing the complex structure of our "galactic ecosystem." Radio maps of the galaxy disk, combined with optical and infrared data, allow astronomers to deduce the spiral pattern of our galaxy. The segments near the Sun are part of a spiral pattern that continues throughout the disk. However, the maps show that the spiral arms are rather irregular and interrupted by branches, spurs, and gaps. The stars in Orion, for example, appear to be a detached segment of a spiral arm, a spur (Figure 9.10). Significant sources of error exist in the mapping methods, but many of the irregularities along the arms seem real, and images of nearby spiral galaxies show similar features (Figure 9.11). The newest models suggest that the central bulge in our galaxy is elongated into a bar (Figure 9.10). In the next chapter you will learn that such bars are common in spiral galaxies.

density wave theory Theory proposed to account for spiral arms as compressions of the interstellar medium in the disk of the galaxy.

Spiral tracers show that the arms contain young objects, and that suggests active star formation. The radio maps confirm this suspicion by showing that the material needed to make stars, hydrogen gas, is abundant in spiral arms.

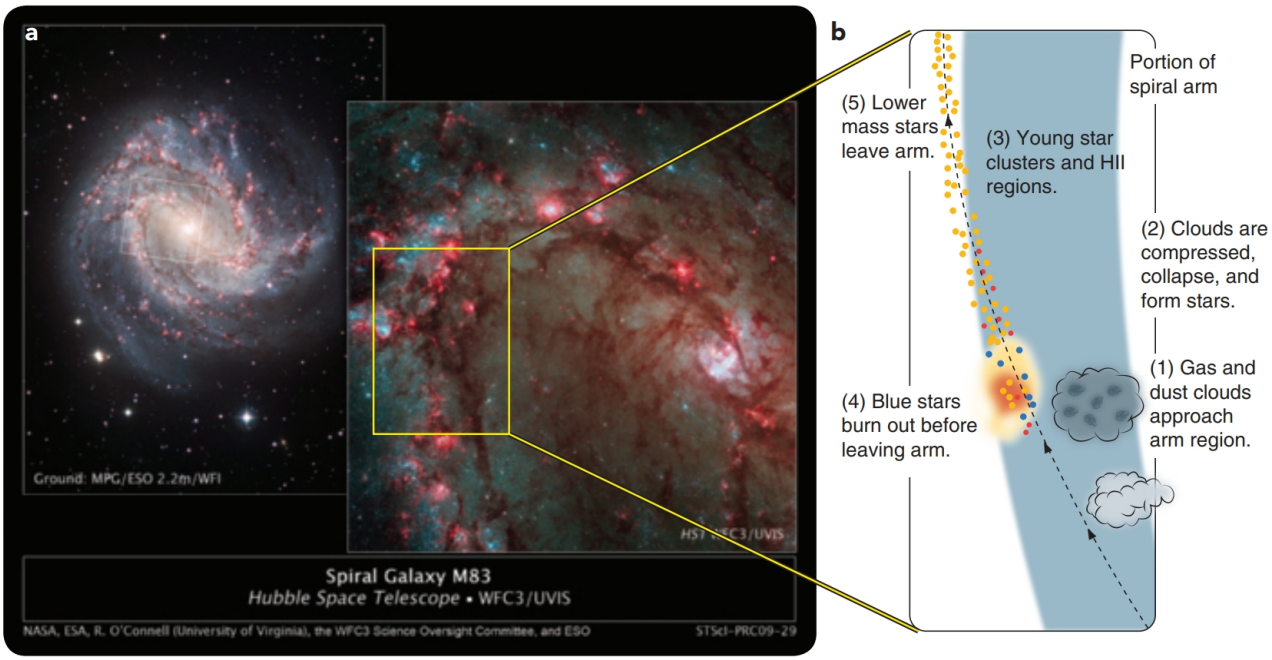
Star Formation in Spiral Arms

Having mapped the spiral pattern, you can ask, "What are spiral arms?" If they were physically connected structures, like a kite string caught on a spinning hubcap, such arms would be wound up and pulled apart by differential rotation within a few tens of millions of years. Yet spiral arms are common in disk-shaped galaxies and must be reasonably permanent features.

The most prominent theory about spiral arms is called the **density wave theory**, which proposes that the arms are waves of compression that move around the galaxy triggering star formation. The density wave is a bit like a traffic jam behind a truck moving slowly along a highway. Seen from an airplane overhead, the jam seems a permanent, though slow-moving, feature. But individual cars overtake the jam from behind, slow down, move up through the jam, wait their turn, pass the truck, and resume speed along the highway. Similarly, clouds of gas overtake the spiral density wave, become compressed in the "traffic jam," and eventually move out in front of the arm, leaving the slower-moving density wave behind.

Star formation will occur where the gas clouds are compressed. Stars pass through the spiral arms unaffected, like bullets passing through a wisp of fog, but large clouds of gas slam into the spiral density wave and are suddenly compressed. Figure 9.11b demonstrates how this movement occurs. In Chapter 7, you saw that sudden compression could trigger the formation of stars in a gas cloud. Thus, new stars should form along the

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Hubble image: NASA, ESA, R. O'Connell (University of Virginia), B. Whitmore (Space Telescope Science Institute), M. Dopita (Australian National University), and the Wide Field Camera 3 Science Oversight Committee; ground-based image: European Southern Observatory

Figure 9.11 (a) Many of the galaxies in the sky are disk shaped, and most of those galaxies have spiral arms. In the close-up photograph (right) of part of the spiral arm of the M83 galaxy (the square area in the left photo) you can see pink HII regions and blue reflection nebulae. Images of other galaxies show that spiral arms are marked by hot, luminous stars that must be very young and nebulae associated with star birth. This should make you suspect that spiral arms are related to star formation. (b) According to the spiral density wave theory, star formation occurs as gas clouds pass through spiral arms.

spiral arms. The spiral arms are not wound up by differential rotation because they are patterns, not physically connected structures.

The brightest stars, the O and B stars, live such short lives that they never travel far from their birthplace and are found only along the arms. Their presence is what makes the spiral arms glow so brightly, due to both their own light and the emission from clouds of gas excited by UV radiation from the stars (Figure 9.11a). Lower-mass stars such as the Sun live longer and have time to move out of the arms and continue their journey around the galaxy. The Sun may have formed in a star cluster almost 5 billion years ago when a gas cloud smashed into a spiral arm. Since that time, the Sun has escaped from its birth cluster and made about 20 trips around the galaxy, passing through spiral arms many times.

The density wave theory is very successful in explaining general properties of spiral galaxies, but it has two problems. First, what stimulates the formation of the spiral pattern in the first place? Theorists calculate that minor fluctuations in the galaxy's disk shape or gravitational interactions with passing galaxies may be able to start a density wave. Second, the density wave theory does not account for the branches and spurs in the spiral arms of our own and other galaxies. The solution to this second problem may lie in a process that sustains star formation once it begins.

Some galaxies are dominated by two spiral arms, with minor irregular spurs and branches. Computer simulations show that the spiral density wave can generate the two-armed, grand-design pattern, but self-sustained star formation may be responsible for the irregularities. Many spiral galaxies do not appear to have two dominant spiral arms, but have abundant spurs and branches that suggest star formation is proceeding robustly in such galaxies. Observations indicate that our Milky Way Galaxy's spiral pattern is intermediate between these two examples.

Star formation can control the shape of spiral patterns as the birth of stars in a cloud of gas can cause the birth of more new stars. Massive stars evolve so quickly that their lifetimes are only an instant in the history of a galaxy, and then they explode as supernovae. You learned in Chapter 7 that bursts of luminosity and jets from newborn stars, and the expanding gases of supernova explosions, can compress neighbouring clouds of gas and trigger more star formation. This

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process is known as **self-sustaining star formation**. The Orion complex, consisting of the Great Nebula in Orion and the protostars buried deep in the dark interstellar clouds behind the nebula, seems to be a region of self-sustaining star formation (see **Visualizing Astronomy 7.2, Star Formation in the Orion Nebula**).

Astronomers have built spiral structure models using stars only, which do not successfully match observations. When the gas was introduced into models, the dynamics of interstellar medium became more realistic, allowing a spiral density wave as a natural consequence. Differential rotation of the galaxy could drag the inner edge of a star-forming region ahead and let the outer edge lag behind to produce a cloud of star formation shaped like a segment of a spiral arm. Self-sustaining star formation in combination with differential rotation may produce the branches and spurs so prominent in some galaxies, including our own, but only the spiral density wave can generate the beautiful two-armed grand spiral patterns.

9.3 The Origin and History of the Milky Way

Just as paleontologists reconstruct the history of life on Earth from the fossil record, astronomers try to reconstruct our galaxy's past from the fossil it left behind as it formed and evolved. That fossil is the spherical component of the galaxy. The stars in the halo formed when the galaxy was young. The chemical composition and the distribution of these stars can provide clues to how our galaxy formed.

self-sustaining star formation The process by which the birth of stars compresses the surrounding gas clouds and triggers the formation of more stars.

population I star Stars rich in atoms heavier than helium; nearly always relatively young stars found in the disk of the galaxy.

population II star Stars poor in atoms heavier than helium; nearly always relatively old stars found in the halo, globular clusters, or the central bulge.

metals In astronomical usage, all atoms heavier than helium.

The Age of the Milky Way

To begin, you can easily answer the question of how old are the oldest star clusters. But that easy answer is hard to interpret because there are uncertainties.

The oldest open clusters have ages of about 9 to 10 billion years (see **Visualizing Astronomy 8.1, Star Cluster H–R Diagrams**). These ages, determined by analyzing the turnoff point in the cluster H–R diagram, are somewhat uncertain. Nevertheless, from open clusters you can get a rough age for the disk of our galaxy of at least 9 billion years.

Globular clusters have faint turnoff points in their H–R diagrams and are clearly old, but finding their ages accurately is difficult. Clusters differ slightly in chemical composition, which must be accounted for in calculating the stellar models from which ages are determined. Also, to find the age of a cluster, astronomers must know the distance to the cluster. Precise parallaxes from the *Hipparcos* satellite have allowed astronomers to increase the precision of the Cepheid variable stars' calibration, and careful studies with the newest large telescopes have refined the cluster H–R diagrams. Globular cluster ages seem to average about 11 billion years, with the oldest being a bit over 13 billion years old. The halo of our galaxy therefore seems to be at least 13 billion years old—older than the disk.

Stellar Populations

In the 1940s, astronomers realized there were two types of stars in the galaxy. They were most accustomed to studying the first type, the stars located in the disk, such as stars near the Sun. These they called **population I stars**. The stars of the second type, called **population II stars**, are usually found in spherical components of the galaxy: in globular clusters in the halo, or in the central bulge.

The stars of the two populations fuse nuclear fuels and evolve in nearly identical ways. They differ only in their abundance of atoms heavier than helium, atoms that astronomers refer to collectively as **metals**. (Note that this is definitely not the way the word *metal* is commonly used by non-astronomers.) Population I stars are relatively metal rich, containing 2 to 3 percent metals. Population II stars are metal poor, containing only about 0.1 percent metals or less. The metal content of a star defines its population.

Population I stars, sometimes called *disk population stars*, have circular orbits in the plane of the galaxy (Figure 9.8) and are relatively young stars that formed within the last few billion years. The Sun is a population I star. Population II stars belong to the spherical component of the galaxy and are sometimes called *halo population stars*. These stars have randomly tipped orbits with a wide range of shapes. A few follow circular orbits, but most follow elliptical orbits (Figure 9.7); however, all of them orbit around the galactic centre. The population II stars are all lower-mass main-sequence stars or giants. They are old stars. The metal-poor globular clusters are part of the halo population. Since the discovery of stellar populations, astronomers have realized that there is a gradation between populations, as illustrated in Table 9.1.

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Table 9.1 | Stellar Populations

	Population I		Population II	
	Extreme	**Intermediate**	**Intermediate**	**Extreme**
Typical Location	Spiral arms; Thin disk	Thick disk	Central bulge	Halo
Metal content (%)	3	1–2	0.1–1	Less than 0.1
Orbit shape	Circular	Slightly eccentric	Moderately eccentric	Highly eccentric
Range of ages (yr)	0–0.2 billion	0.2–8 billion	8–12 billion	12–13 billion

Why do the disk and halo stars have different metal abundances? The two types of stars must have formed at different stages in the life of the galaxy—specifically, at times when the chemical composition of the galaxy differed. This is a clue to the history of our galaxy, but to use this clue, you must understand the cycle of element building.

The Element-Building Cycle

The atoms of which you are made were created in a process that spanned a number of generations of stars. The process that built the chemical elements over the history of our galaxy led to the possibility of Earth and life on Earth.

You saw in Chapter 8 how elements heavier than helium but lighter than iron are built up by nuclear reactions inside evolving stars. More massive atoms are made only by short-lived nuclear reactions that occur during a supernova explosion. This explains why lower-mass atoms like carbon, nitrogen, and oxygen are more common and why more massive atoms—such as gold, silver, platinum, and uranium—are so rare and, often, valuable. Figure 9.12a shows the abundance of the chemical elements, but notice that the graph has an exponential scale. To get a feeling for the true abundance of the elements, you should draw this graph using a linear scale as in Figure 9.12b. With that scale you see how rare the elements heavier than helium really are.

Most of the matter in stars is hydrogen and helium. Other elements, including carbon, nitrogen, oxygen, and the rest of what astronomers call metals, were cooked up inside stars. When the galaxy first formed, there should have been no metals because stars had not yet manufactured

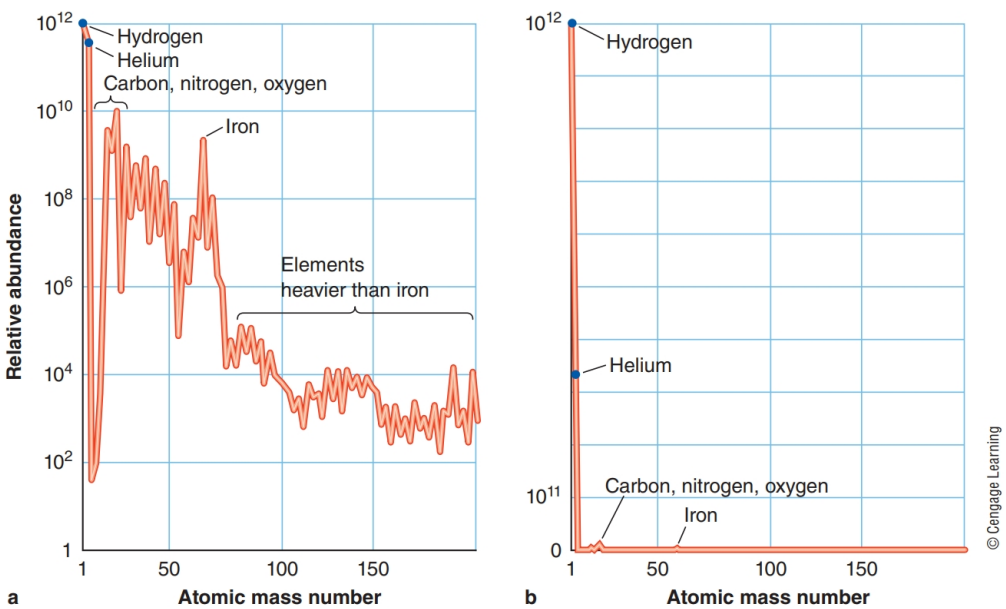


Figure 9.12 The abundance of the elements in the universe. (a) When the elements are plotted on a logarithmic scale, you see that elements heavier than iron are about a million times less common than iron and that all elements heavier than helium (referred to by astronomers as metals) are quite rare. (b) The same data plotted on a linear scale provide a more realistic impression of how rare the metals are. The vertical axis runs from zero to a trillion (10^{12}) mark for hydrogen; helium is around the 300 billion mark. Carbon, nitrogen, and oxygen make small peaks near atomic mass 15, and iron is just barely visible in the graph.

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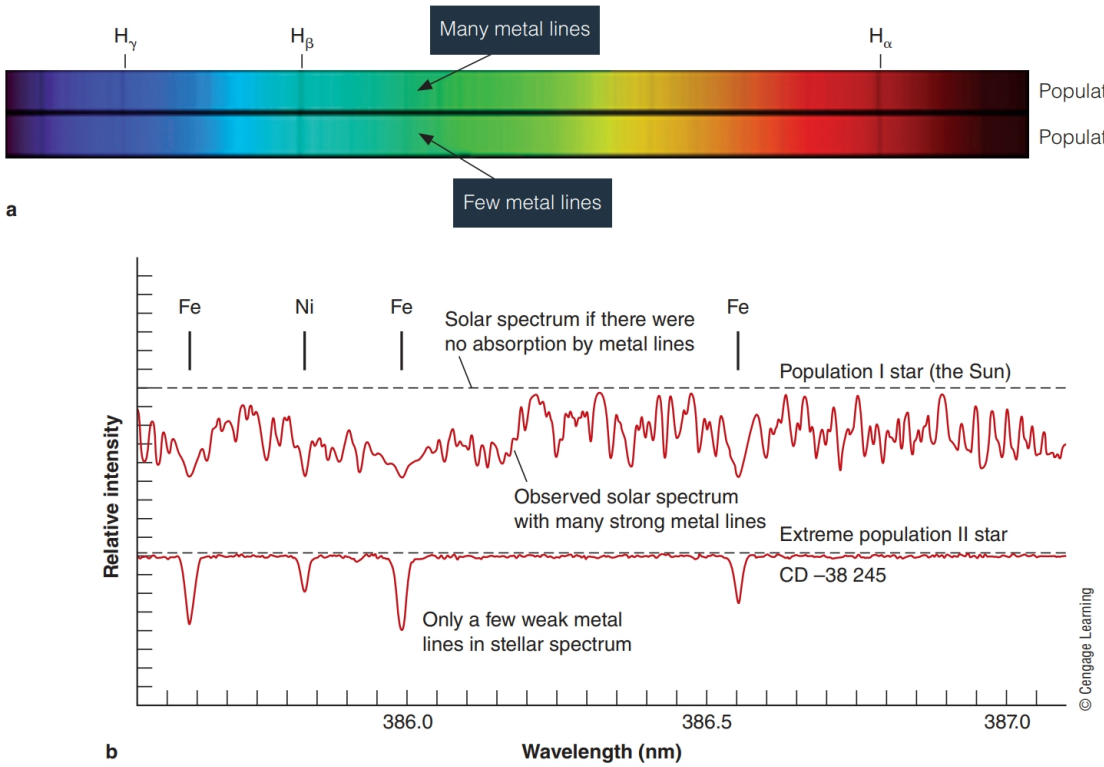


Figure 9.13 (a) The difference between spectra of Population I stars and Population II stars is dramatic. Examine the upper spectrum here and notice the hundreds of faint spectral lines. The lower spectrum has fewer and weaker lines. (b) A graph of such spectra reveals overlapping absorption lines of metals completely blanketing the Population I spectrum. The lower spectrum is that of an extremely metal-poor star with only a few weak metal lines of iron (Fe) and nickel (Ni). This Population II star contains about 10,000 times less metal than the Sun.

any. Judging from the composition of stars in the oldest clusters, the gas from which the galaxy originally condensed must have contained about 90 percent hydrogen atoms and 10 percent helium atoms. The hydrogen and helium came from the big bang that began the universe, which you will study in Chapter 11.

The first stars to form from this gas were metal poor, and now, 13 billion years later, their spectra still show few metal lines. Of course, they may have manufactured many atoms heavier than helium in their cores, but because the stars' interiors are not mixed, those heavy atoms stay trapped at the centres of the stars where they were produced and do not affect the spectra (Figure 9.13). The population II stars in the halo are the survivors of an earlier generation of stars that formed in the galaxy.

Most of the first stars evolved and died, and various types of star death throes, including supernovae, enriched the interstellar gas with metals. Succeeding generations of stars formed from gas clouds that were more enriched, and each generation added to the enrichment with its death. By the time the Sun formed, roughly 5 billion years ago, the element-building process had added about 1.6 percent metals. Since then, the metal abundance has increased further, and stars forming at the present time incorporate 2 to 3 percent metals and become extreme population I stars. Consequently, metal abundance varies between populations because heavy atoms were produced in successive generations of stars as the galaxy aged.

The oxygen atoms you are breathing, the carbon atoms in your flesh, and the calcium atoms in your bones were all created in the interiors of red and yellow giant stars hot enough to sustain fusion reactions beyond helium. The gold and silver atoms in your jewellery and dental fillings and the iodine atoms in your thyroid gland were all created in a few moments during supernova explosions, because those are the only places in the universe hot enough to make these types of atoms. This idea is perhaps the most significant one to take away from an introductory astronomy course and textbook—you, and everything on Earth, are made of stardust.

The History of the Milky Way Galaxy

The lack of metals in the spherical component of the galaxy tells you it is very old, a fossil left behind by the

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galaxy when it was young and drastically different from its present disk shape. The study of element-building and stellar populations leads to the fundamental question, "How did our galaxy form?"

The problem of the formation of our galaxy is still in the stage when there are few competing hypotheses, each explaining a number of observed phenomena, but not one is sufficient on its own. Astronomers can't observe the evolution of a galaxy on the scale of billions of years. The best they can do is analyze the age and composition of stars and stellar clusters in our galaxy, look at the images of other galaxies in different eras of the universe, and construct models.

In the 1950s, astronomers began to develop a **monolithic collapse model**, or "top-down" hypothesis, to explain the formation of our galaxy. Recent observations are forcing a major re-evaluation and revision of that traditional hypothesis.

The traditional hypothesis says that the galaxy formed from a single large cloud of turbulent gas over 13 billion years ago. Stars and star clusters that formed from this material went into randomly shaped and randomly tipped orbits. These first stars were metal poor because no stars had existed earlier to enrich the gas with metals. In this way, the initial contraction of a large, turbulent gas cloud produced the spherical component of the galaxy.

The second stage of this hypothesis accounts for the disk component. The turbulent motions would eventually have cancelled out, leaving the cloud with uniform rotation. A rotating, low-density cloud of gas cannot remain spherical. A star is spherical because its high internal pressure balances its gravity, but in a low-density cloud, the pressure cannot support the weight. Like a blob of pizza dough spun in the air, such a cloud must flatten into a disk as it rotates (Figure 9.14).

This contraction into a disk took billions of years, with the metal abundance gradually increasing as generations of stars were born from the gradually flattening gas cloud. The stars and globular clusters that formed first in the halo would not have been affected by the motions of the gas and would have been left behind by the cloud as it collapsed and flattened. Later generations of stars formed in flatter distributions. The gas distribution in the galaxy now is so flat that the youngest stars are confined in a thin disk only about 300 ly thick. These stars are metal rich and have nearly circular orbits.

This monolithic collapse hypothesis accounts for many of the Milky Way's properties. Advances in technology, however, have improved astronomical observation and, beginning in the 1980s, contradictions between theory and observation arose. For example, not all globular clusters have the same age, but, surprisingly, some of the younger clusters seem to be in

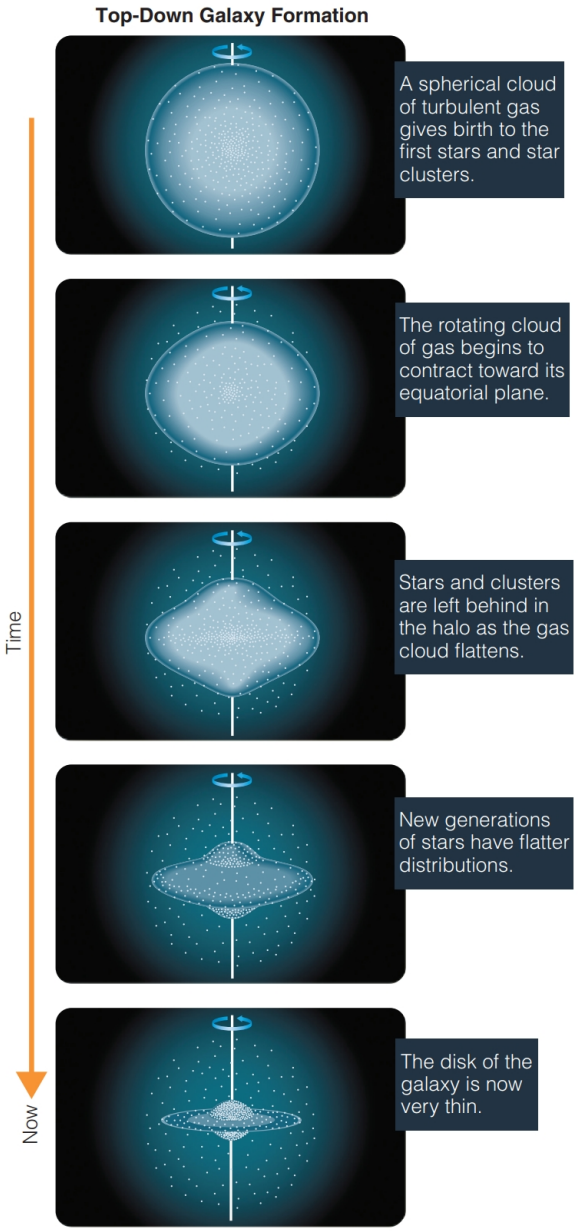


Figure 9.14 The monolithic collapse, or top-down, model for the origin of our galaxy begins with a spherical gas cloud that flattens into a disk.

the outer halo. In contrast, the monolithic collapse hypothesis says that the halo formed first and predicts that the clusters within it should either have a uniform age or the most distant ones should be slightly older. Another problem is that the oldest stars are observed to be metal poor but not completely metal free. There must have been at least a

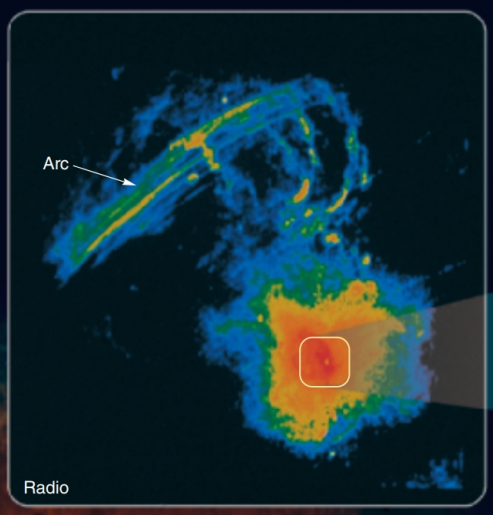
monolithic collapse model
An early hypothesis that says the galaxy formed from the collapse of a single large cloud of turbulent gas over 13 billion years ago.

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Visualizing Astronomy 9.1
Sagittarius A*

1

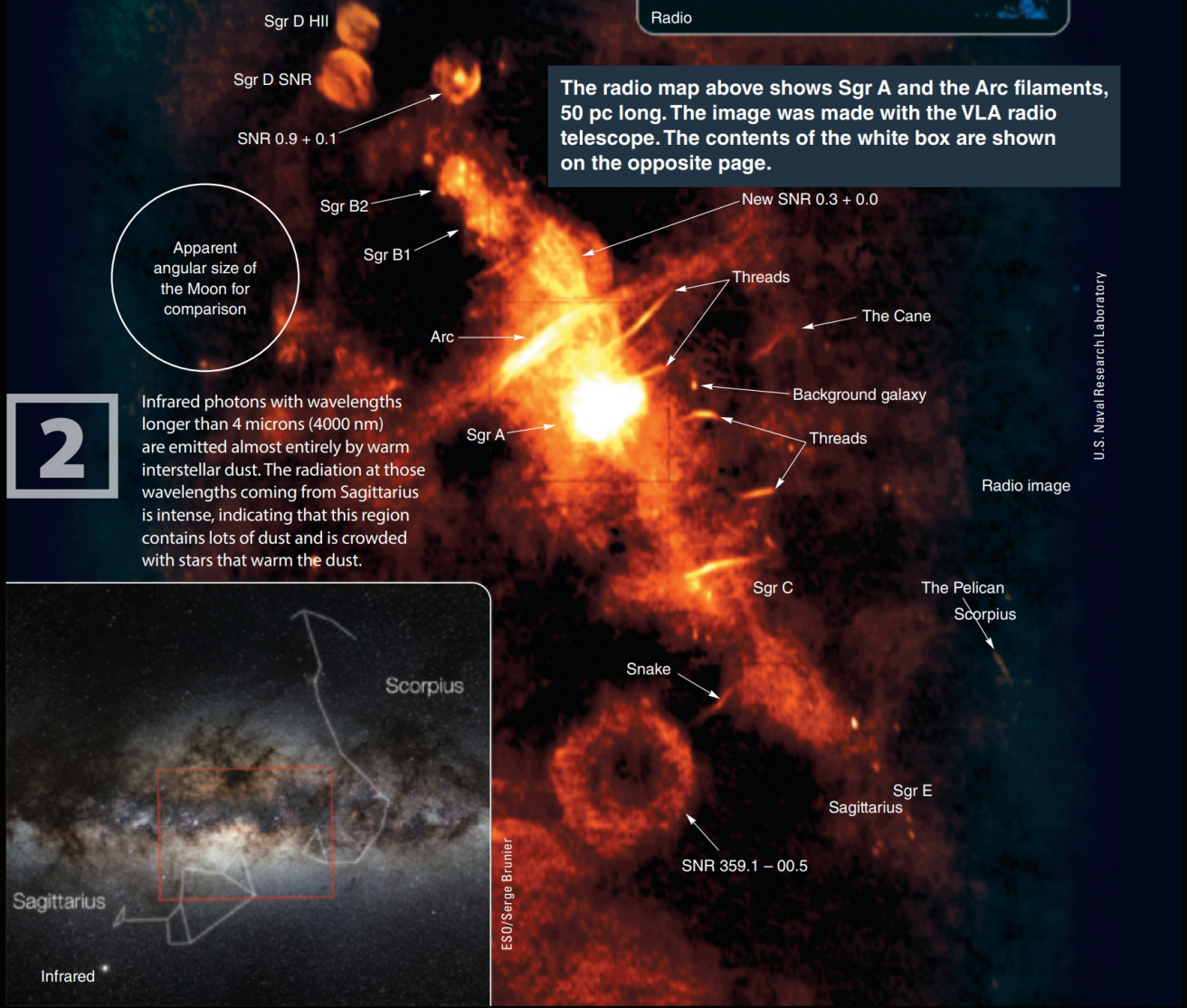
So much interstellar dust exists in the plane of the Milky Way that you cannot observe the nucleus of our galaxy at visual wavelengths. The image below is a radio image of the innermost 1000 ly. Many of the features are supernova remnants (labelled SNR), and a few are star formation clouds. Peculiar features such as threads, the Arc, and the Snake may be gas trapped in magnetic fields. At the centre of the image lies the strong radio source Sagittarius A (Sgr A), the location of the nucleus of our galaxy.



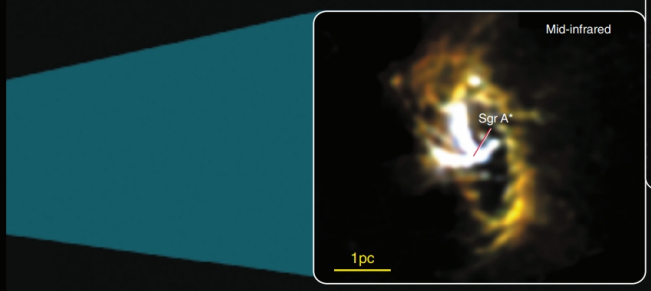
The radio map above shows Sgr A and the Arc filaments, 50 pc long. The image was made with the VLA radio telescope. The contents of the white box are shown on the opposite page.

2

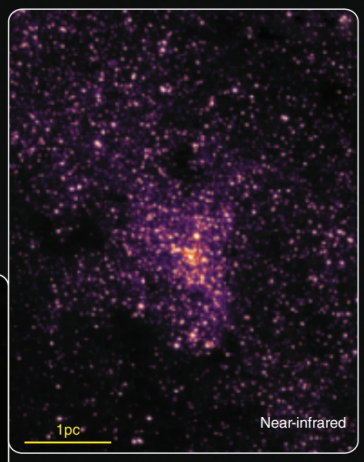
Infrared photons with wavelengths longer than 4 microns (4000 nm) are emitted almost entirely by warm interstellar dust. The radiation at those wavelengths coming from Sagittarius is intense, indicating that this region contains lots of dust and is crowded with stars that warm the dust.



1a This high-resolution radio image of Sgr A (within the white box in the small-scale map on the opposite page) reveals a spiral swirl of gas around an intense point-like radio source known as Sgr A*. About 10 ly across, this spiral lies in a low-density cavity inside a larger disk of neutral gas. The arms of the spiral are thought to be streams of matter flowing into Sgr A* from the inner edge of the larger disk.



NASA/DLR/SOFIA/FORCAST Team/Lau et al.



NASA/ESA/STScI/AURA/NSF/NICMOS Team

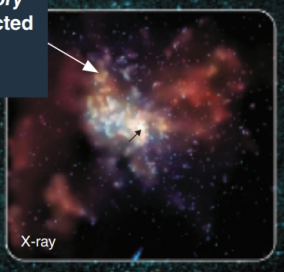
A near-infrared image from the Hubble Space Telescope, showing the same region as the SOFIA mid-infrared image on the left. The dense cluster of stars located inside the circumnuclear cloud ring can be seen at this wavelength (1.9 microns), but the ring itself is too cool to emit significant amounts of near-infrared radiation. Nevertheless, especially dense parts of the ring can be discerned in this image as shadowy patches of obscuration. Sgr A* is located in the middle of the central star cluster.

An image of the central few parsecs of our galaxy obtained by astronomers on board the Stratospheric Observatory for Infrared Astronomy (SOFIA), combining data at mid-infrared wavelengths of 20, 32, and 37 microns. This image contains the region of the white box within the radio image on the opposite page. A ring of gas and dust clouds is observed that surrounds a relatively empty central zone. The bright y shape represents heated material apparently falling from the cloud ring into the centre. Sgr A* is located at the intersection of the arms of the y.

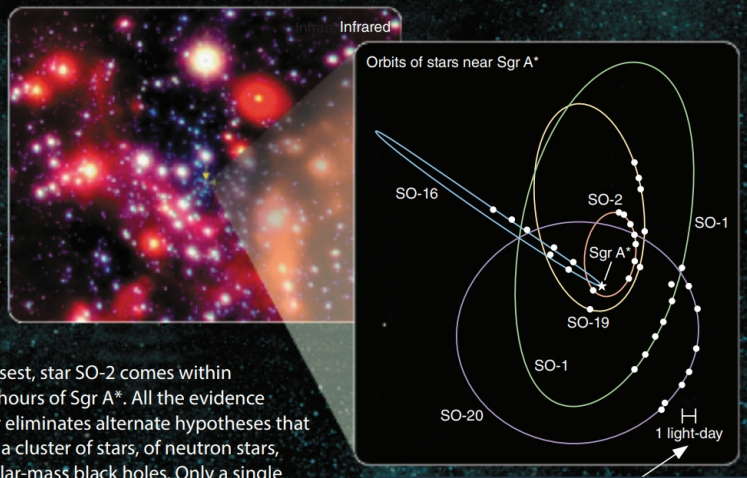
3 Evidence of a Black Hole in the Nucleus of Our Galaxy

Astronomers have been able to use large infrared telescopes and adaptive optics to follow the motions of stars orbiting around Sgr A*. A few of those orbits are shown here. The size and period of the orbit allows astronomers to calculate the mass of Sgr A* using Kepler's third law. The orbital period of the star SO-2, for example, is 15.2 years, and the semi-major axis of its orbit is 950 AU. The motions of the observed stars indicate that Sgr A* has a mass of 4 million solar masses.

The *Chandra X-ray Observatory* has imaged Sgr A* and detected more than 2000 other X-ray sources in the area.



NASA/CXC/SAO/MIT/F. K. Baganoff et al.



ESO/MPE/S. Gillessen et al.

3a A black hole with a mass of 4 million solar masses would have an event horizon with a size on the scale of this diagram smaller than the period at the end of this sentence. A slow dribble of only 0.0002 *M* of gas per year flowing toward the black hole could produce the observed energy. A sudden increase, such as when a star falls in, could produce a violent eruption.

At its closest, star SO-2 comes within 17 light-hours of Sgr A*. All the evidence together eliminates alternate hypotheses that Sgr A* is a cluster of stars, of neutron stars, or of stellar-mass black holes. Only a single supermassive black hole could contain so much mass in such a small region.

For comparison, the diameter of the planetary region of our Solar System, defined by Neptune's orbit, is half a light-day.

The evidence of a massive black hole at the centre of our galaxy seems conclusive. It is much too massive to be the remains of a dead star, however, and astronomers conclude that it probably formed as the galaxy first took shape.

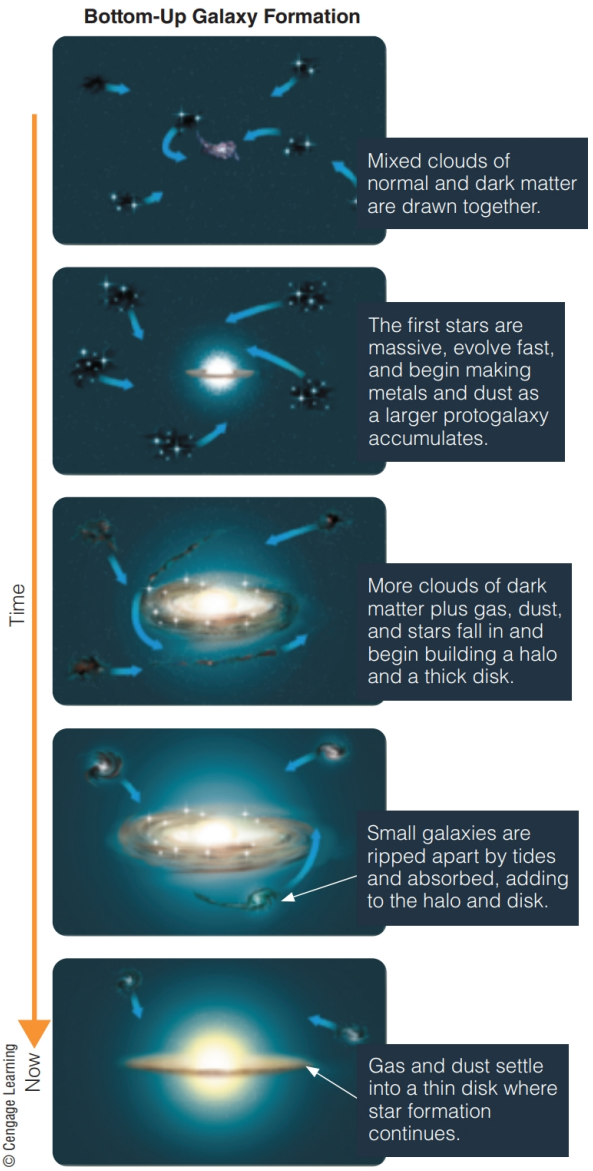


Figure 9.15 The bottom-up hypothesis for the formation of the Milky Way Galaxy proposes that smaller star systems accumulated to form larger ones. To see how this could have built our galaxy, start with the first frame, only a few hundred million years after the beginning of the universe: small clouds of matter begin accumulating and stars begin forming in them. In the second frame, the central object has grown larger, and in the third frame, the galactic halo and disk are forming. By the last frame, representing today, the disk of the galaxy has become very thin.

few massive stars to create these metals during a generation before the formation of the oldest stars now seen in the halo.

Can the original hypothesis be modified to explain these observations? Perhaps the galaxy began with the contraction of a gas cloud to form the central bulge, and the halo later accumulated from gas clouds that had been slightly enriched in metals by an early generation of massive stars. That first generation of stars would have formed from almost pure hydrogen and helium gas, which mathematical models indicate would form only stars with very high masses. Those stars would have lived very short lives, made metals, and died in supernova explosions; none would be left today. This would explain the metals in the oldest stars surviving today.

There is also evidence that entire small galaxies were captured by the growing Milky Way, and that fresh gas was added to the disk in several episodes over the life of the galaxy; it did not form during a single gravitational collapse. An alternative bottom-up hypothesis proposes that our galaxy was assembled from smaller objects (Figure 9.15). If our galaxy absorbed a few small but partially evolved galaxies, some of the globular clusters in the halo may be hitchhikers that originally belonged to the captured galaxies. This could explain the range of globular cluster ages and compositions. The next chapter explains that such galaxy mergers do occur.

The problem of the formation of our galaxy is frustrating because the explanations are incomplete. The older monolithic collapse hypothesis has proven inadequate to explain all of the observations, and you see astronomers attempting to refine the observations and devise new theories. The metal abundances and ages of the stars in our galaxy seem to be important clues, but metal abundance and age do not tell the whole story. In the next section you will learn that the nucleus of our galaxy, like in many other galaxies, contains a mysterious and massive object capable of powerful outbursts that could have profoundly influenced galactic evolution.

9.4 The Nucleus

The most mysterious region of our galaxy is its very centre, the nucleus. At visual wavelengths, this region is totally hidden by gas and dust that dim the light by 30 magnitudes. If a trillion (10^{12}) photons of visible light left the centre of the galaxy on a journey to Earth, only one would make it through the gas and dust. The longer-wavelength infrared photons are scattered much less often: One in every ten makes it to Earth. Consequently, visual-wavelength observations reveal nothing about the nucleus, but it can be observed at longer wavelengths, such as in the infrared and radio parts of the spectrum.

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Observations of the Galactic Nucleus

Harlow Shapley's study of globular clusters placed the centre of our galaxy in Sagittarius, and the first radio maps of the sky showed a powerful radio source located in Sagittarius. The first infrared map of the central bulge made by Eric Becklin in 1968 showed the location of intense radiation where the stars are most crowded together, which identified the gravitational centre of the galaxy. Later high-resolution radio maps of that stellar centre revealed a complex collection of radio sources, and one of those sources—**Sagittarius A*** (abbreviated SgrA* and pronounced "sadge A-star")—was at the expected location of the galactic core.

Observations show that SgrA* is only a few astronomical units in diameter but is a powerful source of radio energy. The tremendous amount of infrared radiation coming from the central area appears to be produced by crowded stars and by dust warmed by those stars. But the question was, what could be as relatively tiny as SgrA* and produce so much radio energy?

Study **Visualizing Astronomy 9.1, Sagittarius A***, and notice three important points:

1. Observations at radio wavelengths reveal complex structures near SgrA* that are caused by magnetic fields and by rapid star formation. Supernova remnants show that massive stars have formed there recently and died explosively.
2. The centre is very crowded. Tremendous numbers of stars and radiation from SgrA* heat the dust, producing strong infrared emission.
3. There is evidence that SgrA* is a supermassive black hole into which gas is flowing.

From 1992 to 2008, German astronomers continuously followed 28 stars in the vicinity of the galactic centre using the European Southern Observatory at La Silla, Chile (see the graph in **Visualizing Astronomy 9.1, Sagittarius A***). UCLA Milky Way Center Group did a similar observation, with 17 stars, using the Keck telescope on Mauna Kea, Hawaii. Using orbital characteristics of stars and Kepler's laws, the teams calculated the, mass of a central object responsible for very high velocities of stars. The most plausible explanation for the estimated 4.1 million solar masses concentrated within a small volume is a supermassive black hole. One of the stars, named SO-2, which orbits every 16 years, passed very close to the black hole in May 2018. In July 2018, the GRAVITY collaboration of the VLA telescope in Chile detected the shift in a star's light caused by the extreme gravity of the black hole called gravitational redshift, confirming one of the predictions of Einstein's general theory of relativity.

Astronomers continue to test the hypothesis that the centre of our galaxy contains a supermassive black hole. Such an object is sufficient to explain the observations, but is it necessary? Is there some other way to explain what is observed? So far, the only hypothesis that seems adequate is that our galaxy's nucleus is home to a supermassive black hole.

Meanwhile, observations are allowing astronomers to improve their models. For instance, SgrA* is not as bright in X-rays as it should be if it had a hot accretion disk with matter constantly flowing into the black hole. Observations of X-ray and infrared flares lasting only a few hours suggest that mountain-size blobs of matter may occasionally fall into the black hole and be heated and ripped apart by tidal forces (see Chapter 8). The black hole may be mostly dormant and lack a fully developed hot accretion disk because the rate of matter flow into it is relatively low at the present time.

Such a supermassive black hole could not be the remains of a single dead star. It contains much too much mass. It probably formed when the galaxy first formed over 13 billion years ago. In the next chapter you will learn that supermassive black holes are commonly found in the centres of galaxies.

Sagittarius A* The powerful radio source located at the core of the Milky Way Galaxy.

The **Big Picture**

Hang on tight. The Sun, with Earth in its clutches, is ripping along at high velocity as it orbits the centre of the Milky Way Galaxy, our "parent" galaxy. Except for hydrogen atoms, which have survived unchanged since the universe began, you and Earth are made of metals, atoms heavier than helium. All of these atoms were cooked up by stars during their life—or death—throughout the history of our galaxy. Each generation of stars has produced elements heavier than helium and spread them into the interstellar medium. The abundance of metals has grown slowly in the galaxy. About 4.6 billion years ago a cloud of gas enriched by heavy atoms slammed into a spiral arm and produced the Sun, Earth—and you.

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Review and Discussion Questions

Review Questions

1. How do you know you live in a galaxy?
2. How do you know ours is a spiral galaxy, and what are the spiral arms?
3. Where is most of the dust and gas concentrated in our galaxy?
4. Why are Cepheid variable stars important in our study of the Milky Way galaxy?
5. How did our galaxy form and evolve?
6. What lies at the very centre of our galaxy?
7. Why didn't astronomers before Shapley realize how large the galaxy is?
8. What is the evidence that our galaxy contains a large amount of dark matter?
9. Contrast the motion of the disk stars and that of the halo stars. Why do their orbits differ?
10. Why are all spiral tracers young?
11. Why couldn't spiral arms be physically connected structures? What would happen to them?
12. Why does self-sustaining star formation produce clouds of stars that look like segments of spiral arms?
13. Why are metals less abundant in older stars than in younger stars?
14. Why do the disk and halo stars have different metal abundances?
15. What evidence contradicts the monolithic collapse hypothesis for the origin of our galaxy?
16. Why are stellar populations an important factor in determining the formation process of the galaxy?
17. What does rotational curve suggest about the content of our galaxy?
18. Describe the kinds of observations you would make to study the galactic nucleus.
19. Why must astronomers use infrared telescopes to observe the motions of stars around SgrA*?
20. What evidence can you cite that the nucleus of the galaxy contains a supermassive black hole?

Discussion Questions

1. How would the information in this chapter differ if interstellar dust did not block starlight?
2. Why doesn't the Milky Way circle the sky along the celestial equator or the ecliptic?

Learning to Look

1. Why does the galaxy shown below have so much dust in its disk? How big do you suppose the halo of that galaxy really is?



NASA/Hubble Heritage Team/STScI/AURA

2. Why are the spiral arms in the galaxy below blue? What colour would the halo be if it were bright enough to see in this photo?



NASA/Hubble Heritage Team and A. Riess, STScI

STUDY TOOLS

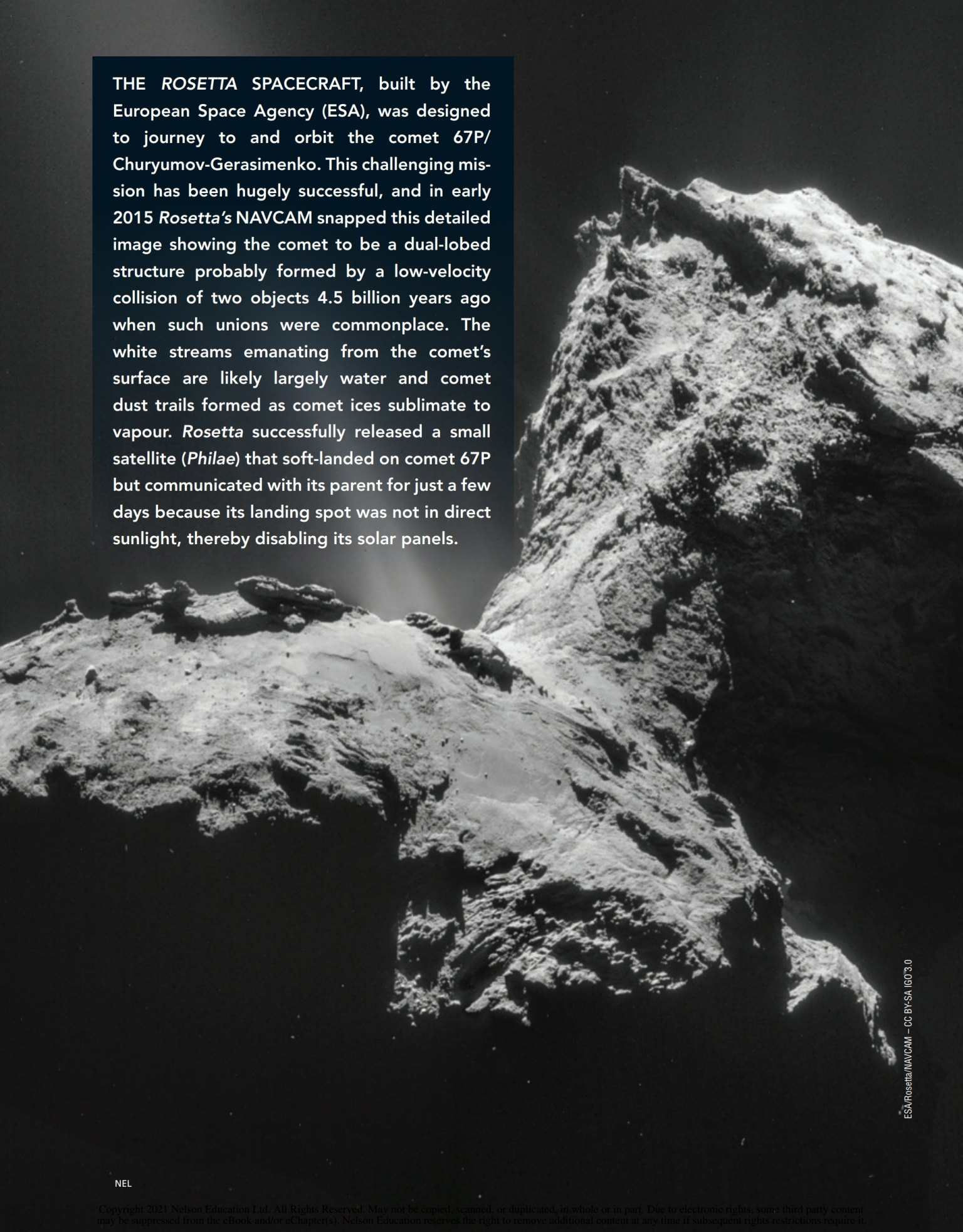
IN THE BOOK

- Tear Out the Review Card on *The Milky Way Galaxy.*

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THE *ROSETTA* SPACECRAFT, built by the European Space Agency (ESA), was designed to journey to and orbit the comet 67P/Churyumov-Gerasimenko. This challenging mission has been hugely successful, and in early 2015 *Rosetta's* NAVCAM snapped this detailed image showing the comet to be a dual-lobed structure probably formed by a low-velocity collision of two objects 4.5 billion years ago when such unions were commonplace. The white streams emanating from the comet's surface are likely largely water and comet dust trails formed as comet ices sublimate to vapour. *Rosetta* successfully released a small satellite (*Philae*) that soft-landed on comet 67P but communicated with its parent for just a few days because its landing spot was not in direct sunlight, thereby disabling its solar panels.

ESA/Rosetta/NAVCAM – CC BY-SA IGO 3.0

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PART THREE

10 Galaxies



CHAPTER OUTLINE

10.1 The Family of Galaxies
10.2 The Distribution of Galaxies in the Universe
10.3 The Masses of Galaxies and Dark Matter
10.4 The Evolution of Galaxies
10.5 Active Galaxies, Quasars, and Supermassive Black Holes

GUIDEPOST

The Milky Way Galaxy is only one of a few trillion galaxies visible in the sky. In this chapter you will learn about different kinds of galaxies and their complex histories and violent eruptions, and you will find answers to several important questions:

- How do astronomers know what galaxies are like?
- Why are there different kinds of galaxies?
- Do other galaxies contain dark matter and supermassive black holes, as does our own galaxy?
- How are galaxies distributed in the universe and what does that teach us about the evolution of galaxies and structures in the universe?
- Why do some galaxies produce tremendous eruptions?

Less than a century ago, astronomers did not know that galaxies exist. Nineteenth-century telescopes revealed faint nebulae scattered among the stars, some with spiral shapes. Astronomers argued about the nature of these nebulae, but it was not until the 1920s that astronomers understood that many of those nebulae are other galaxies much like our own, and it was not until recent decades that astronomical telescopes could reveal the variety, intricacy, and beauty of the galaxies. In this chapter, you will learn current theories about the formation and evolution of galaxies and discover that the amount of gas, dust, and dark matter

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Every object in this image is a galaxy.

Science progresses best when observations force us to alter our preconceptions.

Vera Rubin

True knowledge exists in knowing that you know nothing.

Socrates (c. 470–399 BCE)

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in a galaxy is a critical clue. You will also discover that interactions between galaxies can dramatically influence their structure and evolution.

A number of theories about the evolution of galaxies are conflicting and open for debate, not finalized. However, the basis of building a theory of evolution of galaxies is basic data gathering. You can classify the different kinds of galaxies and discover their fundamental properties: diameter, luminosity, and mass. After you know the typical properties of galaxies, you can start to build models about their origin and evolution.

This chapter also covers some of the most energetic events in the universe—in particular, that the energy pouring out of the nuclei of certain galaxies is enormously greater than explosions of supernovae.

10.1 The Family of Galaxies

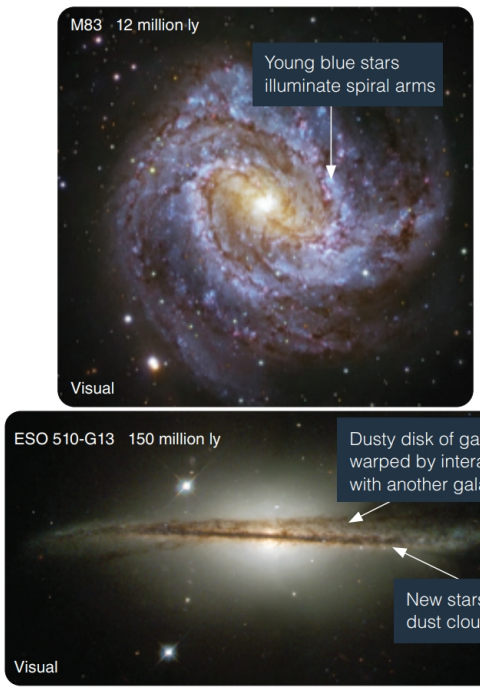
Astronomers classify galaxies according to various properties. Creating a system of classification is fundamental technique in science (see **How Do We Know? 10.1**). Classification according to their shape was developed in the 1920s by Edwin Hubble (after whom the Hubble Space Telescope is named). Study **Visualizing Astronomy 10.1, Galaxy Classification**. You will notice the following important points:

1. There are galaxies with no disk, no spiral arms, and almost no gas, dust, or new stars forming. These are elliptical galaxies, and they range in size and mass from small dwarfs to huge, massive giants.
2. Disk-shaped galaxies usually have spiral arms that are either less or more prominent, and generally large amounts of gas and dust and ongoing stellar formation.
3. Some galaxies have an irregular shape, with gas, dust, and star-forming nebulae; they include the Milky Way's neighbours, the **Large Magellanic Cloud** and the **Small Magellanic Cloud**.
4. Different kinds of galaxies have different colours, depending mostly on how much star formation is happening in them. Spirals and irregulars usually contain plenty of young stars, including massive, hot, luminous O and B stars. They produce most of the light and give spirals and irregulars a distinct blue tint. In contrast, elliptical galaxies usually have few young stars. The most luminous stars in the elliptical galaxies are red giants, which give those galaxies a red tint.

Large Magellanic Cloud The larger of two irregular galaxies visible in the southern sky passing near the Milky Way Galaxy.

Small Magellanic Cloud The smaller of two irregular galaxies visible in the southern sky passing near the Milky Way Galaxy.

You might also wonder what proportion of the galaxies are elliptical, spiral, and irregular, but that is a difficult question to answer. In some catalogues of galaxies about 70 percent are spiral, but that is the result of what scientists call a selection effect (see **How Do We Know? 10.2**). Spiral galaxies contain hot, bright stars and are consequently very luminous and easy to see (Figure 10.1). From careful studies, astronomers conclude that ellipticals are more common than spirals, and irregulars make up about 25 percent of all galaxies. Among spiral galaxies, about two-thirds are barred spirals.



(top): ESO/IDA/Danish 1.5 m/R. Gendler, S. Guisard (www.eso.org/~sguisard) and C. Thöne. (bottom): NASA/ESA/STScI/AURA/NSF/The Hubble Heritage Team, ESO

Figure 10.1 A century ago, photos of galaxies looked like spiral clouds of haze. Modern images of these relatively nearby galaxies reveal dramatically beautiful objects filled with newborn stars and clouds of gas and dust.

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HOW DO WE KNOW? 10.1



Classification in Science

What does classification tell a scientist? Classification is one of the most basic and most powerful scientific tools. Establishing a system of classification is often the first step in studying a new aspect of nature, and it can produce unexpected insights.

Charles Darwin sailed around the world from 1831 to 1836 with a scientific expedition aboard the ship HMS *Beagle*. Everywhere he went, he studied the living things he saw and tried to classify them. For example, he classified different types of finches he saw on the Galapagos Islands based on the shapes of their beaks. He found that those that fed on seeds with hard shells had thick, powerful beaks, whereas those that picked insects out of deep crevices had long, thin beaks. His classifications of these and other animals led him to think about how natural selection shapes creatures to survive in their environment, which led him to understand how living things evolve.

Years after Darwin's work, paleontologists classified dinosaurs into two orders, lizard-hipped and bird-hipped dinosaurs. This classification, based on the shapes of dinosaur hip joints, helped the scientists understand patterns of evolution of dinosaurs. It also led to the conclusion that modern birds, including the finches that Darwin saw on the Galapagos, evolved from dinosaurs.

Astronomers use classifications of galaxies, stars, moons, and many other objects to help them see patterns, trace relationships, and generally make sense of the astronomical world. Whenever you encounter a scientific discussion, look for the classifications on which it is based. Classifications are the orderly framework on which much of science is built.

The distance to a galaxy is the key to finding its diameter and its luminosity. With even a modest telescope and a CCD camera (see Chapter 4, page 83), you could photograph a galaxy and measure its angular diameter. If you know the distance to the galaxy you can find its linear diameter. Also, if you measure the apparent brightness of the galaxy you can use the distance to find its luminosity, as you learned regarding stars in Chapter 6.

The results of such observations show that galaxies differ dramatically in size and luminosity. Irregular galaxies tend to be small, 1 to 25 percent the diameter of our galaxy, and of low luminosity. Although they are common, they are easy to overlook. The Milky Way Galaxy is large and luminous compared with most spiral galaxies, though astronomers know of a few spiral galaxies that are even larger and more luminous. Elliptical galaxies cover a wide range of diameters and luminosities. The largest, called giant ellipticals, are five or more times the diameter of the Milky Way Galaxy, but many so-called dwarf elliptical galaxies are only 1 percent the diameter of our galaxy.

Clearly, the diameter and luminosity of a galaxy do not determine its type. Some small galaxies are irregular, and some are elliptical. Some large galaxies are spiral, and some are elliptical. How many galaxies are there in the visible part of the universe? In the mid-1990s, the Hubble Space Telescope produced a famous photograph—the Hubble Deep Field. The telescope collected photons during hundreds of exposures over ten days from an area of the sky not larger than a grain of sand, a dark spot where nothing had ever been seen through telescopes on Earth. Astronomers uncovered a tremendous number of galaxies. There are good reasons to believe that the region of the sky chosen for study is typical, so evidently the entire sky is carpeted with galaxies. The most recent research effort, called the Hubble Legacy Field survey (see this chapter's opening image) is weaving together images from the Hubble Deep Field, eXtreme Deep Field, and GOODS (Great Observatories Origins Deep Survey), which used the Hubble Space Telescope from infrared to ultraviolet, the Chandra X-ray Observatory, the Spitzer Infrared Space Telescope, and the XMM-Newton X-ray Telescope, as well as the largest ground-based telescopes. The result of the Legacy research is an estimate that at least two trillion galaxies would be visible if today's telescopes were used for an all-sky census.

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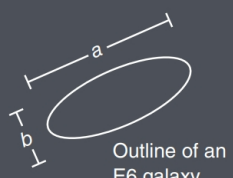
Visualizing Astronomy 10.1
Galaxy Classification

1

Qualitative (morphological) galaxy classification is illustrated below using Hubble's classic "tuning-fork" diagram. Shown here, the main types of galaxies are elliptical (1a) - graded by flattening from ovals E0 to S0 disk galaxies without spiral structure (1b); spiral and barred spiral galaxies (1c) - graded by resolution of arms; and irregular galaxies (1d).

1a **Elliptical galaxies** are round or elliptical, contain no visible gas and dust, and lack hot, bright stars. They are classified with a numerical index ranging from 1 to 7; E0s are round, and E7s are highly elliptical. The index is calculated from the largest and smallest diameter of the galaxy using the following formula, rounding to the nearest integer.

$$\frac{10(a-b)}{a}$$



Outline of an E6 galaxy



NASA, ESA and the Hubble Heritage Team (STScI/AURA); Acknowledgment: P. Cote (Herzberg Institute of Astrophysics) and E. Baltz (Stanford University)

M87 is a giant elliptical galaxy classified as E0 or E1. It is several times larger in diameter than our own galaxy and is surrounded by a swarm of more than 500 globular clusters.



NASA, ESA, STScI and J. Blakeslee (Dominion Astrophysical Observatory)

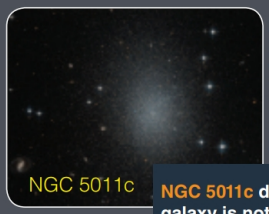


Sloan Digital Sky Survey



ESA/Hubble & NASA. Acknowledgement: J. Barrington, CC BY-SA 3.0 IGO

Galaxies with an obvious disk and nuclear bulge but no visible gas and dust and not-hot, bright stars are called lenticular galaxies, classified as S0 (pronounced "ess zero"). Compare this galaxy with the edge-on spiral in 1b.

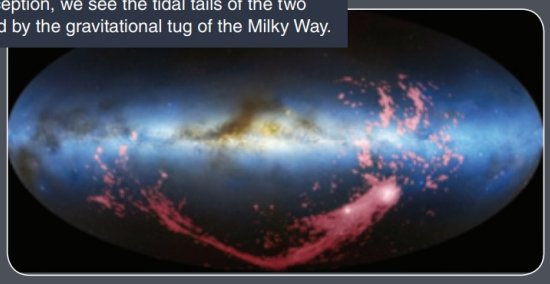


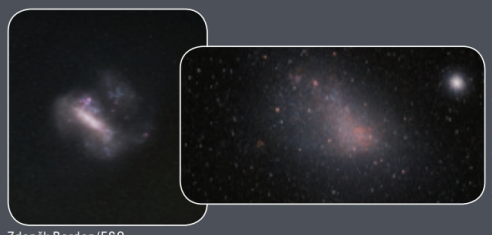
ESA/Hubble & NASA

NGC 5011c dwarf elliptical galaxy is not much bigger than a globular cluster.

1c **Irregular galaxies** (classified Irr) are a chaotic mix of gas, dust, and stars with no obvious nuclear bulge or spiral arms. The Large and Small Magellanic Clouds are visible to the unaided eye as hazy patches in the Southern Hemisphere sky. Telescopic images show that they are irregular galaxies that are interacting gravitationally with our own much larger galaxy. Star formation is rapid in the Magellanic Clouds. stars.

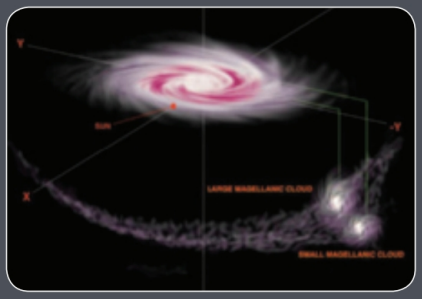
Milky Way and its neighbours, the two irregular galaxies, Small Magellanic Cloud, and Large Magellanic Cloud. In this artistic conception, we see the tidal tails of the two galaxies, created by the gravitational tug of the Milky Way.


© David L. Nidever


ESO/VISTA VMC

Zdeněk Bardon/ESO

Combined radio and visible-light image: the Milky Way is the light blue band in the centre of the image. The brown clumps are interstellar dust clouds in our galaxy. The Magellanic Clouds, satellite galaxies of the Milky Way, are the white regions at the bottom right, with the gaseous stream tidal tail shown in pink.


Dallas Parr. © Copyright CSIRO Australia

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1b **Spiral galaxies** contain a disk and spiral arms. Their halo stars are not visible, but presumably all spiral galaxies have halos. Spirals contain gas and dust and hot, bright O and B stars, as shown below. The presence of short-lived O and B stars alerts us that star formation is occurring in these galaxies. Sa galaxies have larger nuclei, less gas and dust, and fewer hot, bright stars. Sc galaxies have small nuclei, lots of gas and dust, and many hot, bright stars. Sb galaxies are intermediate.



ESA/Hubble & NASA, CC BY-SA 3.0 IGO

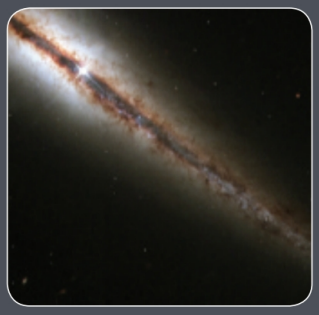


NASA, ESA and the Hubble Heritage Team (STScI/AURA)



European Space Agency & NASA, CC BY-SA 3.0 IGO

Some disk galaxies are rich in dust, which is concentrated along their spiral arms. NGC 4013, shown below, is a galaxy much n its dust is readily apparent.


NASA, ESA and the Hubble Heritage Team (STScI/AURA)

Roughly two-thirds of all spiral galaxies are barred spiral galaxies classified as SBa, SBb, and SBc. They have an elongated nucleus with spiral arms springing from the ends of the bar, as shown at left. The Milky Way Galaxy is a barred spiral with a spiral form between Sb and Sc, so its complete classification is SBbc.



ESO/Oleg Maliy



ESO/IDA/Danish 1.5 m/ R. Gendler, J-E. Ovaldsen, C. Thöne, and C. Feron

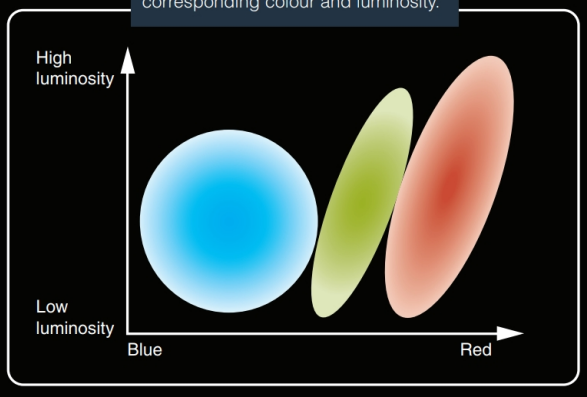


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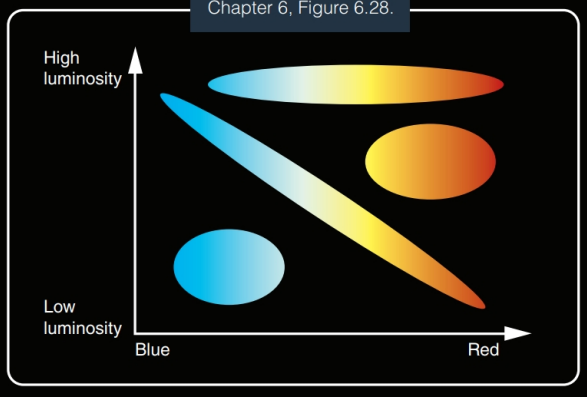
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Quantitative galaxy classification uses a colour-luminosity plot, similar to the H-R diagram. Most galaxies fall into two groups: blue cloud and red sequence. Blue cloud contains mostly spiral and irregular galaxies with an ongoing star formation, hence the blue colour. The red sequence consists primarily of elliptical galaxies, with no star formation, therefore the majority of stars are red in colour.

Graph of galaxy luminosity and colour. The brightest colour represents the number of galaxies with the corresponding colour and luminosity.



H–R diagram for stars, luminosity and colour classification. Refer to Chapter 6, Figure 6.28.



HOW DO WE KNOW? 10.2



Selection Effects in Science

Many different kinds of science depend on selecting objects to study. Scientists studying insects in the rainforest, for example, must choose which ones to catch. They can't catch every insect they see, so they might decide on some way to select the ones they do catch. If they are not careful, a selection effect could bias their data and lead them to incorrect conclusions without their ever knowing it. The reason selection effects are dangerous in science is that they can have powerful influences without always being obvious. Scientists can avoid selection effects only by carefully designing a research project.

For example, suppose you decide to measure the speed of cars on a highway. There are too many cars to measure every one, so you reduce the workload and measure the speed of only red cars. It is quite possible that this selection criterion will mislead you because people who buy red cars may be more likely to be younger and drive faster. Should you measure only brown cars? No, because you might suspect that only older, more sedate people would buy a brown car. Should you measure the speed of any car in front of a truck? Perhaps you should pick any car following a truck? Again, you may be selecting cars that are travelling a bit faster or a bit slower than normal. Only by very carefully designing your experiment can you be certain that the cars you measure are travelling at speeds truly representative of the entire population of cars.

Astronomers face the danger of selection effects quite often. Very luminous stars are easier to see at great distances than faint stars. Spiral galaxies are brighter, bluer, and more noticeable than elliptical galaxies. What astronomers see through a telescope depends on what they notice, and that is powerfully influenced by selection effects.

Scientists engaged in observation must spend considerable time designing their experiments. They must be careful to observe an unbiased sample if they expect to make logical deductions from their results. The scientists in the rainforest, for example, should not catch and study only the red insects. Often, the most brightly coloured insects are poisonous (or at least taste bad) to predators. Catching only brightly coloured insects could produce a highly biased sample of the insect population. Scientists must plan their work with great care and avoid any possible selection effects.

10.2 The Distribution of Galaxies in the Universe

Looking beyond the edge of the Milky Way Galaxy, astronomers find trillions of galaxies. What are the properties of these star systems? What are the diameters, luminosities, and masses of galaxies? Just as you did in studying stellar characteristics (Chapter 6), the first step in studying galaxies is to find out how far away they are. Once we see how galaxies are distributed in the universe we can reveal the structure of matter in the universe, and in turn we can recreate possible scenarios for evolution of galaxies.

distance ladder The calibration used to build a distance scale extending from the size of Earth to the most distant visible galaxies.

Distance Ladder

Astronomers use calibration to build a distance scale reaching from the nearest stars to the most distant visible galaxies (refer to **How Do We Know? 9.1**). This distance scale is often referred to as the **distance ladder** because each step depends on the steps below it (Figure 10.2). The extragalactic distance scale rests on determining luminosities of stars, which is based on measuring stellar parallax (see Chapter 6).

The stellar parallax method is used to determine distances to the nearest stars for which parallax angle can be observed for now; that is, distances up to 1500 light-years. For distances farther than that but within the Milky Way Galaxy, astronomers use the method called main-sequence fitting to determine the distances to clusters of stars by placing the cluster on H–R diagram. Knowing the stars' luminosity and measuring their apparent brightness allows us to determine the distance to the cluster.

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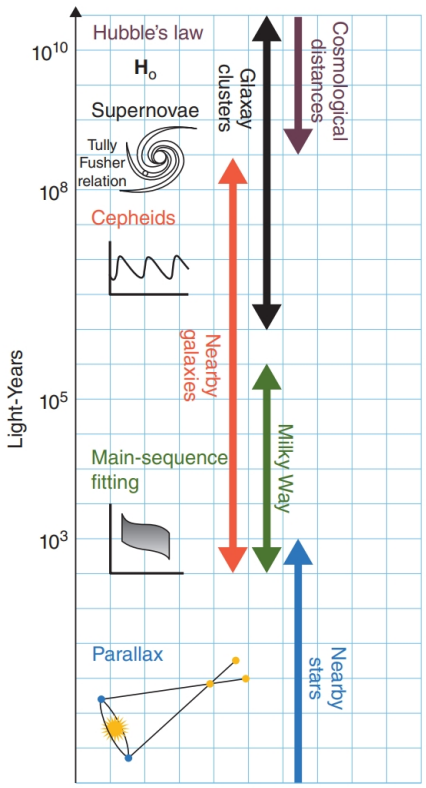


Figure 10.2 Cosmological distance ladder. Different methods are used to measure distances in the universe. Methods higher in the diagram rely on calibrations based on methods lower in the diagram. Note that distances (in light-years) are not linear; they are expressed in power notation.

The distances to galaxies are so large that it is not convenient to express them in light-years or even parsecs. Instead, astronomers use the unit megaparsec (Mpc), or 1 million pc. One Mpc equals 3.26 million ly, or approximately 3×10^{19} km.

To find the distance to a galaxy, today astronomers search among its stars, nebulae, and star clusters for familiar objects whose luminosity they know. Such objects are called **standard candles**. If you can find a standard candle in a galaxy, you can judge its distance.

Cepheid variable stars are reliable standard candles because their period is related to their luminosity (refer to Figure 9.3). If you know the period of a star's variation, you can use the period–luminosity diagram to learn its absolute magnitude (Figure 9.4). Then, by comparing its absolute and apparent magnitudes, you can find its distance. To trust measurements with Cepheids, astronomers first measure the distances to those that are close by using the parallax method. Once the Cepheids are calibrated, astronomers move beyond our Milky Way to nearby galaxies (Figure 10.3). Even with the Hubble Space Telescope, Cepheids are not detectable much beyond 100 million ly, so astronomers must search for other methods and less common but brighter distance indicators, and calibrate them using nearby galaxies containing detectable Cepheids.

standard candle Object of known brightness that astronomers use to find distance—for example, Cepheid variable stars and supernovae.

In the beginning of the 20th century, astronomers were discussing whether spiral nebulae were a part of the Milky Way, its close companions, or perhaps distant galaxies similar to the Milky Way. The debate was settled in the 1920s, when Hubble identified Cepheid variables in the Andromeda nebula M31 (see the current observation in Figure 10.3), and realized that the distances to its Cepheids were so large that Andromeda had to be very far away. He suggested that it was a stellar system—a galaxy—like our own. The scale of the universe dramatically changed. From the view that the universe was contained in our galaxy, it expanded to the picture of immense space in which our Milky Way was just one of the galaxies.



NASA, ESA and the Hubble Heritage Team (STScI/AURA), CC BY-SA 3.0 IGO

Figure 10.3 The Cepheid variable star V1 in the Andromeda Galaxy M31. From a series of images taken on different dates astronomers can locate Cepheids (see inset), determine the period of pulsation, and measure the average apparent brightness. They can then deduce the distance to the galaxy, which is 2.5 million ly for M31.

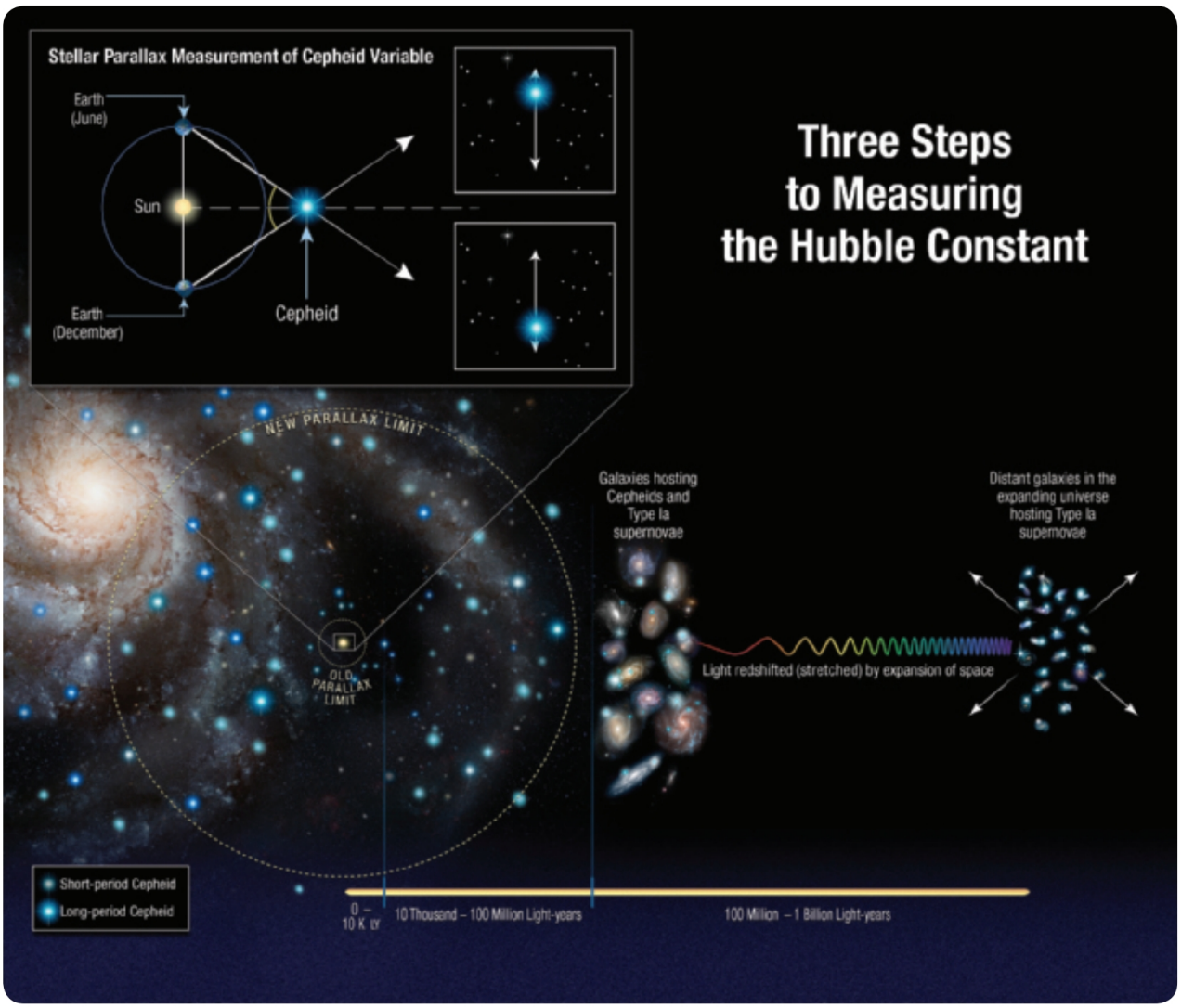
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Tully and Fisher discovered the relationship between luminosity and the rotational rate of spiral galaxies, called the **Tully-Fisher relationship**. If we can resolve the galaxy to see its edges, we can measure the Doppler shift of both sides toward and away from us, thereby determining a galaxy's rotation rate and judging its luminosity for distance calculation.

Tully-Fisher relationship
The linear relation between luminosity and the rotational rate of spiral galaxies used to determine the distance to spiral galaxies as standard candles.

You can see the pattern showing in the "standard candle" method for determining distances. If we know the luminosity of an object and measure its brightness, we can calculate the distance to it.

When a supernova explodes in a distant galaxy, astronomers rush to observe it. Studies show that type Ia supernovae, those caused by the collapse of a white dwarf, all reach about the same luminosity at maximum (which makes them more like "standard bombs" than standard candles). By searching for Cepheids and other distance indicators in nearby galaxies where type Ia supernovae have occurred, astronomers have been able to calibrate these supernovae (Figure 10.4). As a result, when type Ia supernovae are seen in more distant galaxies, astronomers can measure the apparent brightness at maximum and then compare that information with their



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Figure 10.4 This illustration shows the three steps astronomers used to measure the Hubble constant to an unprecedented accuracy, reducing the total uncertainty to 2.3 percent. Calibration (see **How Do We Know? 9.1**) strengthened the construction of the cosmic distance ladder—parallax measurements of Cepheid variables in the Milky Way calibrate the accuracy of distances of Cepheid variables in other galaxies; measurement of Cepheids in galaxies that contain supernovae type Ia and measurement of redshifts for those galaxies calibrate the Hubble law.

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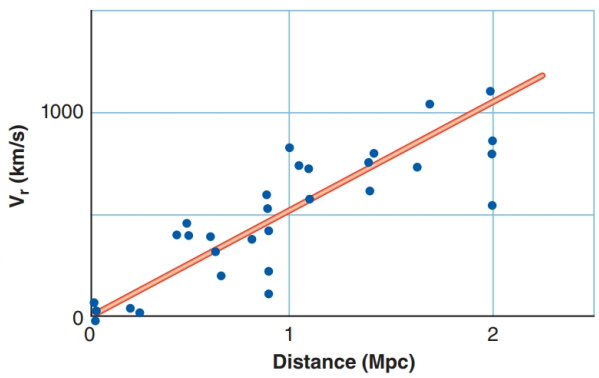
known luminosity to find the distances. Because type Ia supernovae are much brighter than Cepheids, they can be seen in galaxies at great distances. The drawback is that supernovae are rare, and during your lifetime none may occur in a galaxy you are studying. You will see in Chapter 11 how these distance indicators have reshaped our understanding of the history of the universe.

The Hubble Law

Although astronomers find it difficult to measure the distance to a galaxy precisely, they often estimate such distances using a simple relationship. Early in the 20th century, astronomers noticed that the lines in galaxy spectra are generally shifted toward longer wavelengths—that is, redshifted (Chapter 5). These redshifts imply that the galaxies are receding from Earth.

In 1929, Edwin Hubble published a graph that plotted the apparent velocity of recession versus distance for a number of galaxies. The points in the graph fell along a straight line (Figure 10.5). This relation between apparent velocity of recession and distance is known as the **Hubble law**, and the slope of the line is known as the **Hubble constant**, symbolized by H_0.

The Hubble law is important in astronomy for two reasons: to estimate the distance to galaxies, and as evidence that the universe is expanding. The distance to a galaxy can be found by dividing its apparent velocity of recession by the Hubble constant. (Refer to **The Hubble Law** in the Math Reference Cards.) This is a very useful calculation because it is usually possible to obtain a spectrum of a galaxy and measure its redshift even if it is too far away to have observable standard candles. Obviously, knowing the precise value of the Hubble constant is important.



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Figure 10.5 Edwin Hubble's first diagram of the apparent velocities of recession and distances of galaxies did not probe very deeply into space. Although Hubble's distance scale (horizontal axis) was later recalibrated, the diagram did show that the galaxies are receding at speeds proportional to their distances.

Edwin Hubble's original measurement of H_0 was too large because of errors in his measurements of the distances to galaxies. Subsequently, astronomers have struggled to measure this important constant. The most precise measurements of the Hubble constant, made using NASA's infrared Spitzer Space Telescope, yield a value for H_0 of about 23 km/s for every million light-years, or 74.3 km/s/Mpc with an uncertainty of about 3 percent. This means that a galaxy at a distance of 1 million light-years from the Milky Way is receding from us at a rate of 23 km/s, a galaxy 2 million light-years away is receding at 46 km/s, and so on.

Note that the redshifts of galaxies are not really Doppler shifts, even though astronomers often express the redshifts in kilometres per second as if they were true velocities. Today astronomers interpret redshifts of galaxies as caused by the expansion of space carrying galaxies to recede from each other, implying the expansion of the universe. The Hubble law is used to estimate the distance to a galaxy from its redshift. You will see the cosmological implications of the Hubble law in Chapter 11.

Telescopes as Time Machines

The most distant visible galaxies are a little over 10 billion ly away. At such distances you can see an effect like time travel. When you look at a galaxy that is millions of light-years away, you do not see it as it is now but as it was millions of years ago when its light began the journey toward Earth. When you look at a distant galaxy, you look into the past by an amount called the **look-back time**, a time in years equal to the distance to the galaxy in light-years.

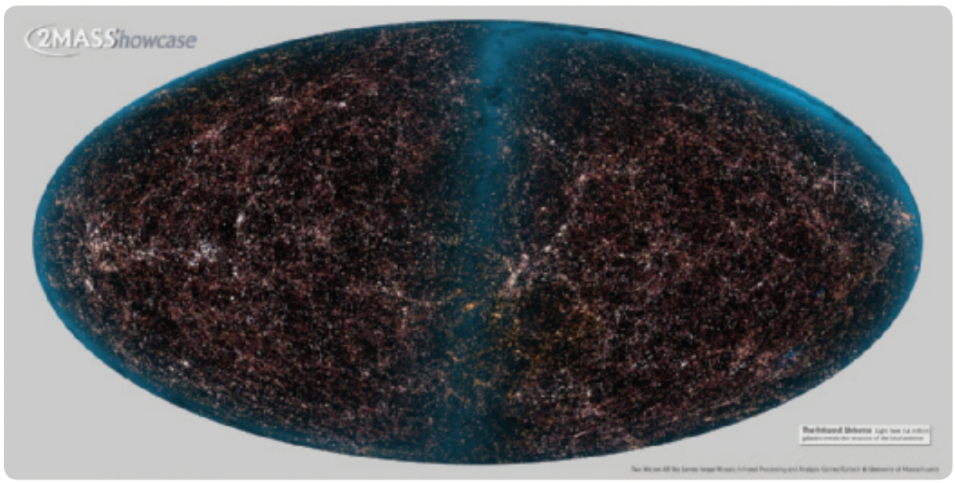
The look-back time to nearby objects is usually not significant. To the Moon it is only 1.3 seconds, to the Sun eight minutes, and to the nearest star about four years. The Andromeda Galaxy has a look-back time of about 2 million years, but that is a mere blink of the eye in the lifetime of a galaxy. When astronomers look at more distant galaxies, the look-back time becomes an appreciable part of the age of the universe. In Chapter 11, you will see evidence that the universe began about 13.8 billion years ago. When astronomers observe

Hubble law The linear relation between the distances to galaxies and the apparent velocity of recession.

Hubble constant A measure of the rate of expansion of the universe; the average value of the apparent velocity of recession divided by distance, about 70 km/s/Mpc.

look-back time The amount by which you look into the past when you look at a distant galaxy; a time that equals the distance to the galaxy in light-years.

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2MASS, T. H. Jarrett, J. Carpenter, & R. Hurt

Figure 10.6 A plot of over one million of the brightest "extended sources" detected by the Two Micron All Sky Survey (2MASS). The vast majority of these sources are galaxies, gravitationally bound together to form clusters, which themselves are loosely bound into superclusters. The vertical blue area is due to bright stars inside our own Milky Way Galaxy.

the most distant visible galaxies, they are looking back over 10 billion years to a time when the universe may have been significantly different.

Organization of Galaxies in the Universe

Equipped with the estimates of distances to the galaxies as far as we can see, we can reveal the structure of matter in the part of the universe that we can observe. Because of look-back time we are also looking at the different eras in the evolution of structures, such as galaxies, in the history of the universe.

In the 1970s, it was noticed that the distribution of galaxies is not entirely random. Galaxies tend to occur in clusters, ranging from a few galaxies to thousands. Clusters are gravitationally held in structures called superclusters, scattered out to the limits of visibility, like in the infrared survey image shown in Figure 10.6. Superclusters and voids (relatively empty regions between them) will be described in Chapter 11, as a cosmic web-like distribution of matter in the universe, which holds important clues about the early universe and the evolution of galaxies (Figure 11.18, page 274).

rich galaxy cluster A cluster containing 1000 or more galaxies, usually mostly ellipticals, scattered over a volume only a few Mpc in diameter.

poor galaxy cluster An irregularly shaped cluster that contains fewer than 1000 galaxies, many of which are spiral, and no giant ellipticals.

Local Group The small cluster of a few dozen galaxies that contains the Milky Way Galaxy.

Examining the structure of various clusters, astronomers noticed two main groups: rich and poor. **Rich galaxy clusters** contain over a thousand galaxies, mostly elliptical, crowded into a spherical volume about 10 million light-years in diameter. The Abel 1689 cluster (located in the direction of constellation Virgo nearly 2.2 billion light-years away from Earth) is an example of a rich cluster, seen in Figure 10.7. It contains mostly E and S0 galaxies (for the types of galaxies, refer to **Visualizing Astronomy 10.1, Galaxy Classification**). Rich clusters often contain one or more giant elliptical galaxies at their centres.

Poor galaxy clusters contain fewer than 1000 galaxies and are irregularly shaped and less crowded toward the centre. Our own **Local Group**, which contains the



ESO/IDA/Danish 1.5 m/ R. Gendler, J-E. Ovaldsen, C. Thöne, and C. Feron

Figure 10.7 Abel 1689, one of the biggest and the most massive galaxy clusters known.

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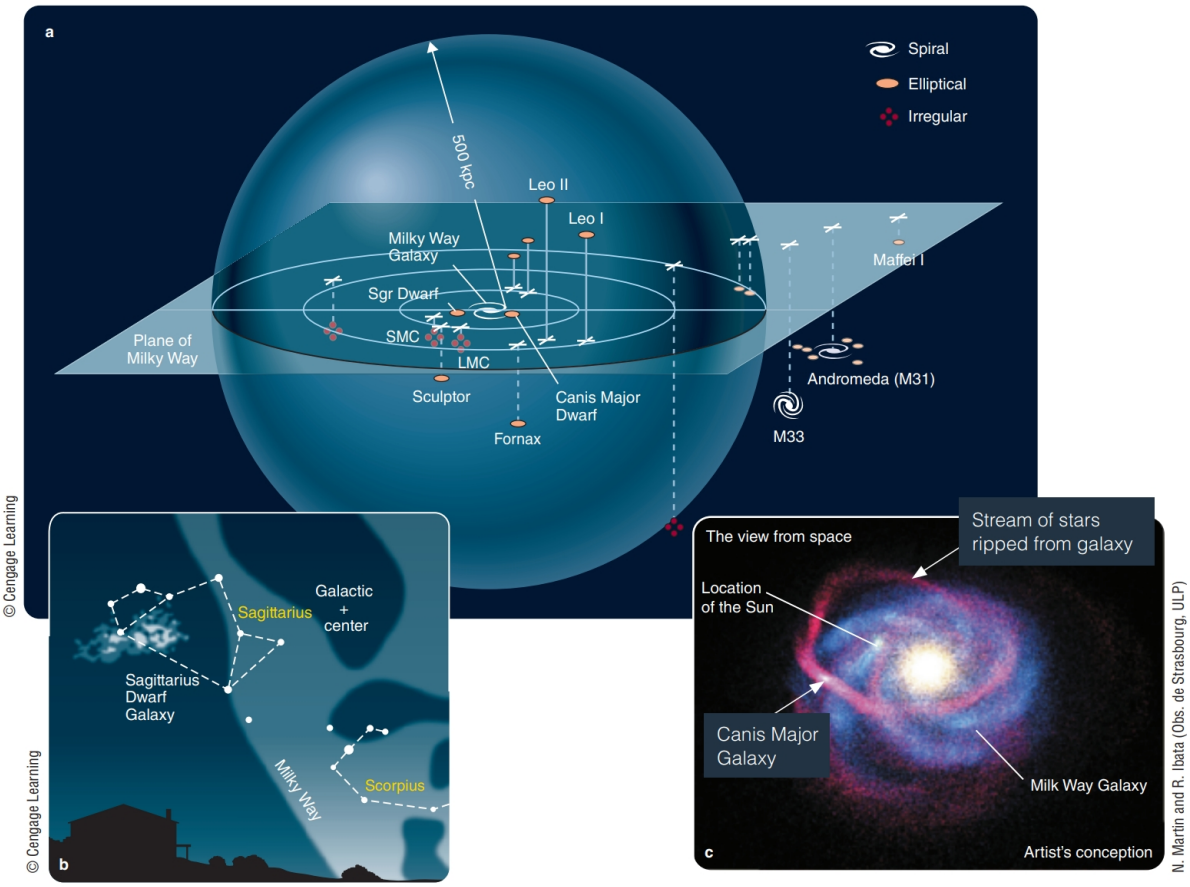


Figure 10.8 (a) The Local Group. Our galaxy is located at the centre of this diagram. The vertical lines giving distances from the plane of the Milky Way are solid above the plane and dashed below. (b) The Sagittarius Dwarf Galaxy (Sgr Dwarf) lies on the other side of our galaxy. If you could see it in the sky, it would be 17 times larger than the full Moon. (c) The Canis Major Dwarf Galaxy, shown in this simulation, is even closer to the Milky Way Galaxy. It is the remains of a small galaxy that is being pulled apart by our galaxy and is hidden behind the stars of the constellation Canis Major.

Milky Way, is a good example of a poor cluster (Figure 10.8). It contains a few dozen members scattered irregularly through a volume slightly more than 3 million ly in diameter. Of the brighter galaxies, 14 are elliptical, three are spiral, and four are irregular.

10.3 The Masses of Galaxies and Dark Matter

The mass of a galaxy is difficult to determine, yet it is one of the most important quantities. It tells you how much matter the galaxy contains, which provides clues to the galaxy's origin and evolution. The masses of galaxies cover a wide range. The least massive contain about a millionth of the Milky Way's mass, and the most massive contain as much as 50 times more mass than the Milky Way. The most common galaxies in the universe are small elliptical galaxies. However, if they are massive, elliptical galaxies are the most massive galaxies of all, and gravitationally dominate in the centres of clusters.

Measuring Masses of Galaxies

The most precise method for measuring the mass of a disk galaxy is called the **rotation curve method** (Figure 10.9). To use this method you need to know (1) the true sizes of the orbits of stars or gas clouds within a galaxy, which requires knowing the distance of that galaxy; and (2) the orbital speeds of the stars or gas clouds, measured from the Doppler shifts of their spectral lines. That is enough information to use Kepler's

rotation curve method A method of determining a galaxy's mass by observing the orbital velocity and orbital radius of stars in the galaxy.

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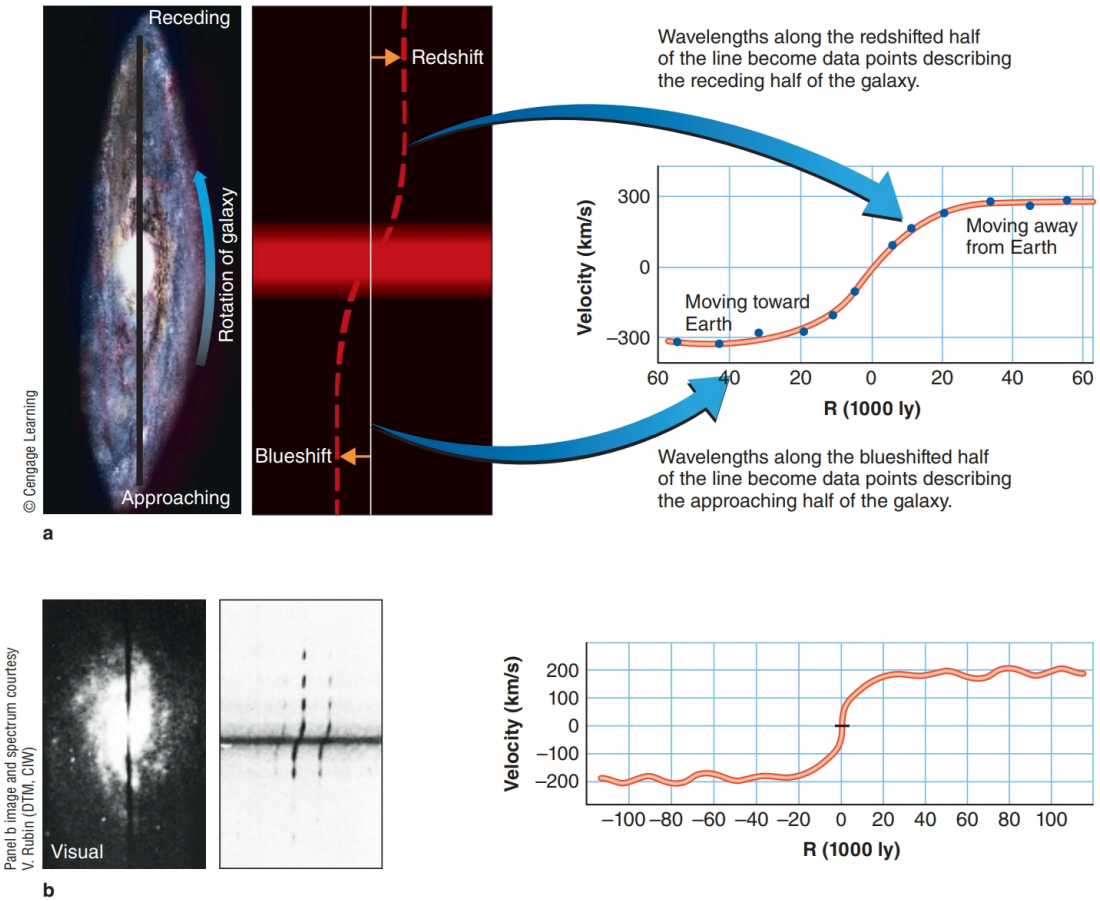


Figure 10.9 (a) In the artwork in the upper half of this diagram, the astronomer has placed the image of the galaxy over a narrow slit so that light from the galaxy can enter the spectrograph and produce a spectrum. A very short segment of the spectrum shows an emission line redshifted on the receding side of the rotating galaxy and blueshifted on the approaching side. Converting these Doppler shifts into velocities, the astronomer can plot the galaxy's rotation curve (right). (b) Real data are shown in the bottom half of this diagram. Galaxy NGC 2998 is shown over the spectrograph slit, and the segment of the spectrum includes three emission lines.

third law and find the mass of the part of the galaxy contained within the star orbits with measured sizes and speeds (Chapter 9). The rotation curve method works only for disk galaxies that are near enough to be well resolved. More distant galaxies appear so small that astronomers cannot measure the radial velocity at different points across the galaxy and must use other less precise methods to estimate masses. Masses of elliptical galaxies are estimated on the basis of the motion of stars, stellar clusters, and gas clouds.

Dark Matter in Galaxies and Clusters of Galaxies

Given the size and luminosity of a galaxy, astronomers can make a rough guess as to the amount of matter it should contain. Adding data for the amount of light stars produce, and how much matter there is between the stars, it should be possible to estimate very roughly the mass of a galaxy from its luminosity. When astronomers measure the masses of galaxies from gravitational effects, they often find that the measured masses are much larger than expected from the luminosities of the galaxies. You discovered this effect in the previous chapter when you studied the rotation curve of our own galaxy and concluded that it must contain large amounts of dark matter, especially in its outer regions (refer to Figure 9.9 page 209).

In the 1930s, Swiss astronomer Fritz Zwicky noticed that in the Coma cluster, the galaxies move so fast that their visible mass would not be sufficient to keep the cluster together. There had to be additional gravity from some invisible matter. Forty years later, analysis of the rotational curves of galaxies indicated the same thing for individual galaxies. The outer parts of galaxies were rotating too fast to be held by gravity of only luminous matter, which we can see and measure in all wavelengths of electromagnetic

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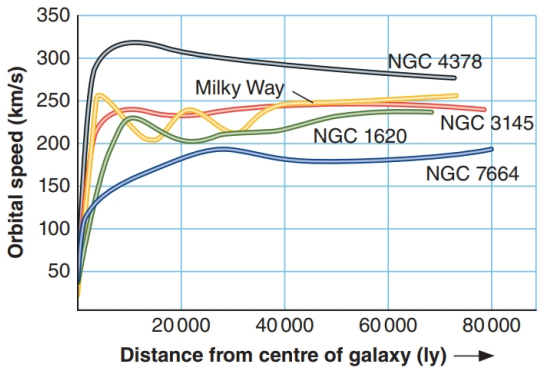


Figure 10.10 All spiral galaxies have similar rotation curves like these four galaxies and the Milky Way. Orbital speeds do not decline at large distances, as you would expect if most of the mass of the galaxy were concentrated toward the centre (see the dotted blue line in Figure 9.9). Rather, the curves are approximately flat at great distances, suggesting the presence of extended halos of dark matter.

spectrum. So there had to be another component of matter that does not show itself through emitting electromagnetic radiation; we call it the dark matter. Australian astronomer Kenneth Freeman measured this paradox by examining galaxy NGC 300, and he was one of the first astronomers to recognize the role and importance of dark matter in spiral galaxies. Estonian astronomer Jaan Einasto conducted the same measurement for our Local Group of galaxies. Soon after, American astronomer Vera Rubin, Canadian Jim Peebles (see Canada's Role in the Global Story of Astronomy box, page 256), and many others around the world confirmed the same findings in other galaxies and clusters. Other spiral galaxies have similarly shaped rotation curves like the Milky Way (Figure 10.10), indicating that measured masses of galaxies amount to 10 to 100 times more mass than you can see.

Masses of clusters of galaxies show even larger discrepancies between visible mass (in all wavelengths) and gravitational mass, which is mass inferred from gravity effects. Estimates of gravitational mass can be done in several ways. The most direct ones are (1) observing galaxies orbiting the massive central elliptical galaxies, and (2) gravitational lensing. Galaxies move like bees around a hive, and from their orbits and velocities we can calculate the mass of a cluster. Gravitational lensing, on the other hand, is the effect a cluster has on light from objects in the background.

Gravitational lensing was first mentioned by Isaac Newton when he postulated that light was composed of particles and that they should be attracted via gravity to masses. Einstein, 200 years after, proposed a theory of gravity called *general relativity*. The origin of gravity, according to general relativity, is the curving of space-time in the presence

gravitational lensing The curving of light by a large mass when the light passes between the source and the observer. Multiple images of the source can be seen.

CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



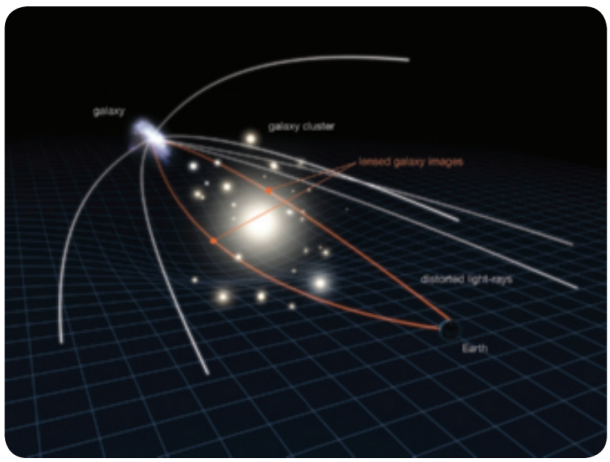
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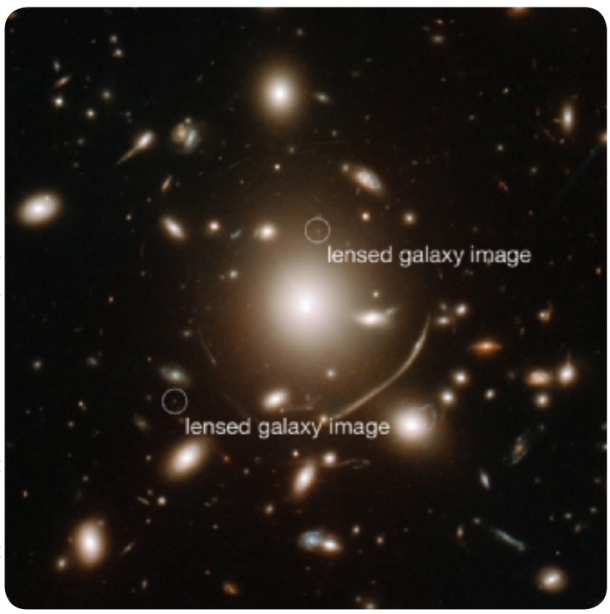
Cygnus X-1

Charles Thomas Bolton

Tom Bolton never expected to discover a black hole. As a postdoctoral researcher at the University of Toronto in 1971, he was observing binary stars at the David Dunlap Observatory in Ontario. He focused on a binary pair in which a blue giant is orbiting its partner, a strong source of X-rays, at unexpectedly high speeds. At first Bolton thought the X-ray source, Cygnus X-1, was a neutron star, but when a colleague suggested that it might be a black hole, his first reaction was disbelief. As he gathered further data, he realized that Cygnus X-1 was too massive to be a neutron star, and could only be a black hole. Matter from the blue star was being pulled into an accretion disk around the black hole, and the inner parts of the disk became hot enough to produce the X-rays observed by Bolton. Meanwhile, two English astronomers published their studies of the same binary pair, but their results were not conclusive. Bolton decided to publish his data and staked his scientific reputation on his claim that Cygnus X-1 was a black hole. The astronomical community was skeptical of this work by a relatively unknown astronomer, and it took another year before it was widely accepted that Bolton had made the first-ever discovery of a black hole. His publication in the journal *Nature* is considered one of the most important astronomy papers ever written. Bolton describes that incredible summer of 1971 as the most exciting time of his career.

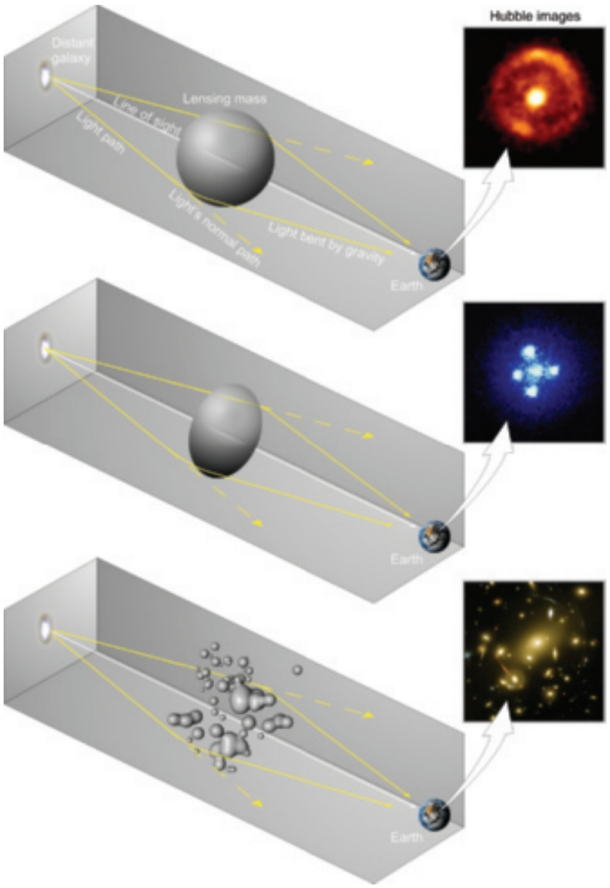
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Source: (a) NASA/JPL (b) NASA/JPL/Marc Postman (STScI)

Figure 10.11 (a) This illustration shows gravitational lensing. Note that the scale is greatly exaggerated in this diagram. In reality, the distant galaxy is much farther away and much smaller. (b) Gravitational lensing in reality. The giant cluster of elliptical galaxies in the centre of this image contains so much dark matter mass that its gravity bends light. The cluster's gravitational field acts as a sort of magnifying glass, bending and concentrating the distant object's light toward us.



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Figure 10.12 Gravitational lenses produce different shaped images depending on the shape of the lensing body. If the lens is spherical then the image appears as an Einstein ring (in other words, as a ring of light) (top); if the lens is elongated then the image is an Einstein cross (it appears split into four distinct images) (middle), and if the lens is a galaxy cluster, like Abell 2218, then arcs and arclets (banana-shaped images) of light are formed (bottom).

of a mass, so that all other masses follow the curvature when they move (refer to Chapter 8.6). Light is also subject to curving. Light from an object—a star or a galaxy, for example—would pass by a mass between the observer and the source (called the lens), curve in the gravity field, and continue in the deflected direction. The observer would see a "mirage" some distance away from the real object; see the drawing in Figure 10.11a and the real image in Figure 10.11b. In perfect alignment where object, lens, and observer are in a straight line, the observer should see an infinite number of images—a ring around the lens. Indeed, this alignment, called Einstein's ring, has been observed (see Figure 10.12, top).

Einstein needed some experimental support when he proposed this strange idea in 1913. The perfect alignment for such observation was a solar eclipse. The Sun, a large mass, would deflect starlight; above all, the stars would be visible in that moment. All that needed to be done was to observe known stars in the moment of total eclipse and measure the deflection. However, you cannot observe a solar eclipse where you live unless your location is due for one. Right after Einstein's proposal,

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expeditions were planned. A few were unsuccessful—for example, German astronomer Erwin Finlay-Freundlich went to Russia in August 1914 to observe an eclipse, but World War I was declared and he was arrested. The first expedition that was able to show light deflection was by British astronomer Sir Arthur Eddington, to Africa; however, the results were not very accurate. The expeditions in the 1950s and radio observations in the 1960s obtained measurements that were in agreement with theoretical predictions.

Clusters of galaxies often have arcs around them, as in the case of Abel 2281 (Figure 10.12, bottom) and Abel 1689 (Figure 10.7). Those are smeared images of an object—for example, a galaxy that lies behind the lensing cluster. These are extreme cases of lensing, and they imply that masses of lenses are enormous. We can calculate, on the basis of images (see Figure 10.12) the orientation of observer–lens–object, as well as the mass of the lens. With this method, masses of clusters of galaxies are found to be incredibly larger than all luminous mass together, in all wavelengths observed and summed up.

With gravitational lens Abell 2281, a team of astronomers have identified and studied a galaxy so far away we see it as it was less than a billion years after the big bang. It is visible as two tiny dots (labelled) on either side of the bright cluster galaxy in the centre of Figure 10.12, bottom. Viewing this galaxy through the gravitational lens meant that the scientists were able to discern many intriguing features of galaxies in the early universe that would otherwise have remained hidden. This has profound implications for our understanding of how and when the first galaxies formed.

Dark matter remains one of the fundamental unresolved problems of modern astronomy. Observations of galaxies and clusters of galaxies reveal that 90 to 95 percent of the matter in the universe is invisible matter and energy. The universe you see—the kind of matter that you and the stars are made of—has been compared to the foam on an invisible ocean. This problem of dark matter will be picked up again in Chapter 11 with a discussion of how dark matter affects the nature of the universe, its past, and its future.

10.4 The Evolution of Galaxies

The test of any scientific understanding is whether you can put all the evidence and theory together to tell the history of the objects studied. Can you describe the origin and evolution of the galaxies? Just a few decades ago it would have been impossible, but the evidence from space telescopes and new-generation telescopes on Earth combined with advances in computer modelling and theory allow astronomers to outline the story of the galaxies.

In Chapter 9, you learned about two models of galaxy formation that can possibly describe the origin of the Milky Way Galaxy: the monolithic collapse model (Figure 9.14) and the bottom-up galaxy formation model (Figure 9.15). Presumably, other spiral galaxies formed in a similar way. But why did some galaxies become spiral, some elliptical, and others irregular? Clues to that mystery lie in the images of the farthest objects, from the early universe.

The Hubble Legacy Field image in Figure 10.13 shows galaxies from 550 million years ago to 13 billion years ago. They range from the youngest (the farthest away from us) to the oldest (the closest to our time). Looking at snapshots of galaxies in each era, astronomers can reconstruct the evolutionary paths of galaxies.

The youngest galaxies, or galactic building blocks, each contain dust, gas, and a few billion stars (Figure 10.13, bottom row.). These young objects could be the ancient building blocks of today's galaxies because they are close enough in space to eventually collide or merge with each other. Each building block is larger than a normal star cluster. Some of them look disrupted, which is an indication that they may be interacting and merging with neighbouring galaxies to form a larger structure: a full-size galaxy. This is a strong support for a bottom-up galaxy formation model. Depending on the density of matter in a protogalaxy, and the interaction between matter and dark matter, galaxies merged out of building blocks into spiral or elliptical galaxies.

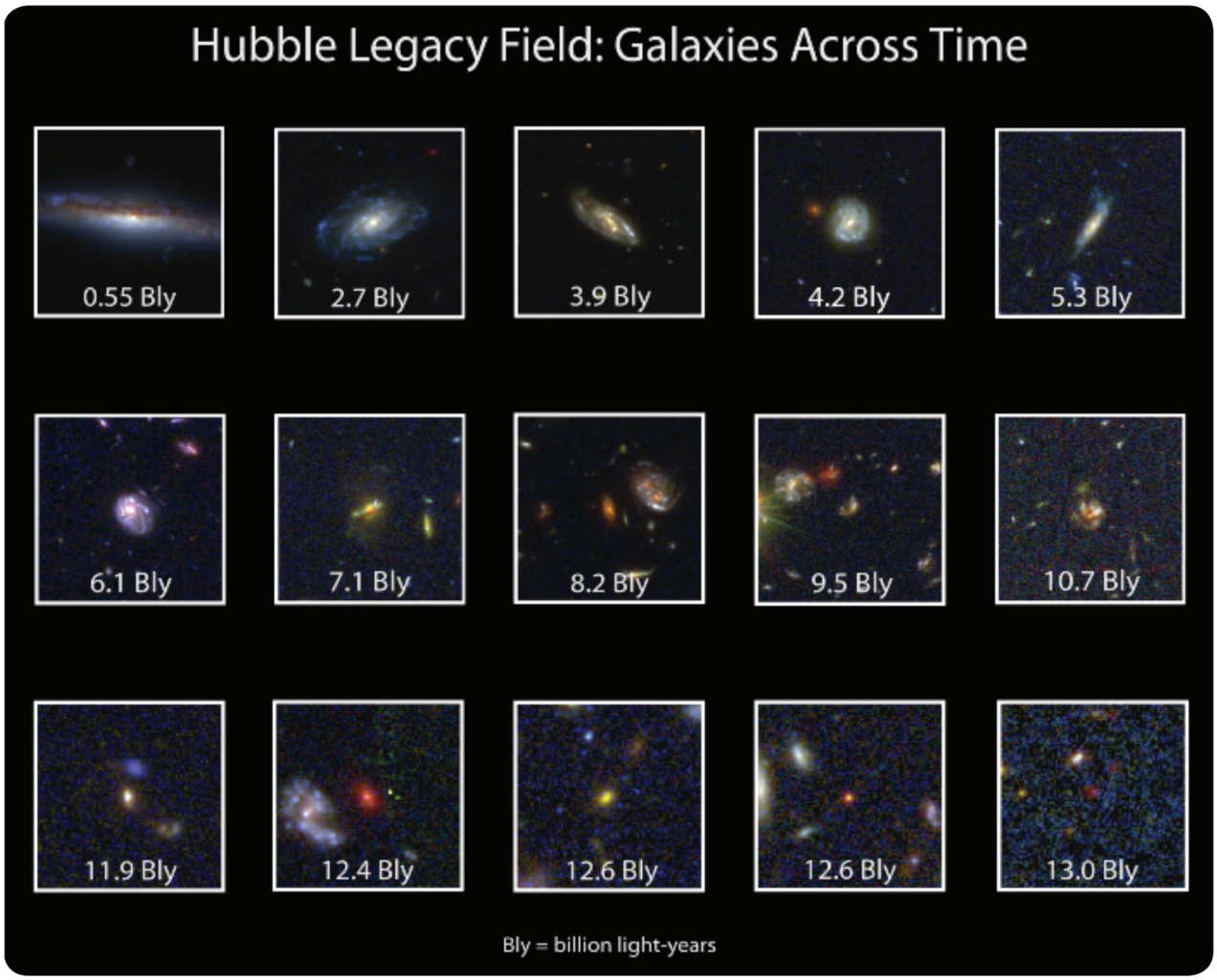
The following sections describe the further evolution of the galaxies through galaxy groupings into clusters and galaxy collisions or mergers.

Colliding Galaxies

Astronomers are finding more and more evidence that galaxies collide, interact, and merge. In fact, collisions among galaxies may dominate their evolution.

Do not be surprised that galaxies collide with each other. The average separation between galaxies is only about 20 times their diameter, so galaxies should bump into each other fairly often, astronomically speaking. In comparison, stars almost never collide because the typical separation between stars is about ten million times their diameter.

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NASA, ESA, G. Illingworth and D. Magee (University of California, Santa Cruz), K. Whitaker (University of Connecticut), R. Bouwens (Leiden University), P. Oesch (University of Geneva), and the Hubble Legacy Field team.

Figure 10.13 A Hubble Legacy Field close-up of images of 15 galaxies from the survey, from 550 million years ago (top panel) to 13 billion years ago (bottom panel). The universe is 13.8 billion years old. The galaxies on the top panel are mature "adult" galaxies, fully developed spirals teeming with stars; the middle panel shows galaxies when they are growing and changing dramatically; and the bottom panel shows small, young galaxies, so far away that we see them as they looked less than 1 billion years after the big bang. The look-back time is shown at the bottom of each image.

A collision between two stars is about as likely as a collision between two gnats flitting about in a baseball stadium.

When two galaxies collide they can pass through each other without stars colliding. Gas clouds and magnetic fields do collide, but the biggest effects may be tidal. Even when two galaxies just pass near each other tides can cause dramatic effects, such as long streamers called **tidal tails** (Figure 10.14).

tidal tail A long streamer of stars, gas, and dust torn from a galaxy during its close interaction with another passing galaxy.

When a galaxy swings past a massive object such as another galaxy, tides are severe. Stars near the massive object try to move in smaller, faster orbits, while stars farther from the massive object follow larger, slower orbits. Such tides can distort a galaxy or even rip it apart, as seen in the Mice Galaxies (Figure 10.15).

In some cases, two galaxies can merge and form a single galaxy, with intense star formation triggered by the collision, like the Cartwheel Galaxy (Figure 10.16).

Newest observations of interacting galaxy clusters show a large presence of dark matter. Abell 520 was formed when two clusters of galaxies merged due to collision. The optical images in Figure 10.17 show, in orange, galaxies (NASA's Hubble Space Telescope) and starlight from galaxies (Canada-France-Hawaii Telescope). Green regions show hot gas from the collision (NASA's Chandra

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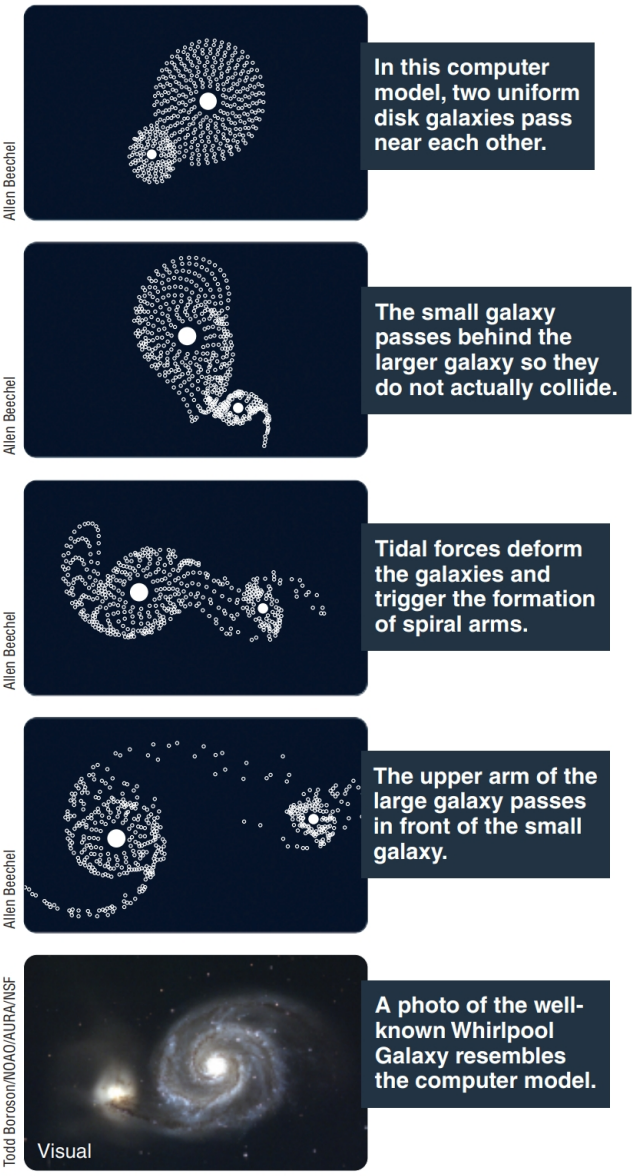


Figure 10.14 Computer simulation of galaxy interaction.



Figure 10.15 The Mice Galaxies are pulling each other apart. They have likely already passed through each other and will probably collide again and again until they coalesce.



Figure 10.16 The Cartwheel Galaxy was once a normal galaxy but is now a **ring galaxy**. One of its smaller companions has plunged through it at a high speed almost perpendicular at the galaxy's disk. That has triggered a wave of star formation, and the more massive stars have exploded, leaving behind black holes and neutron stars. Some of those are in X-ray binaries, and that makes the outer ring bright in X-rays.

X-ray Observatory). Gravitational lensing reveals that most of the mass of the cluster is dominated by dark matter, shown in blue-green.

The largest elliptical galaxies appear to be the product of galaxy mergers, which triggered star formation that used up the gas and dust. In fact, astronomers see a high level of star formation in many galaxies. These **starburst galaxies** are very luminous in the infrared because a collision has triggered a burst of star formation that is heating the dust. The warm dust reradiates the energy in the infrared. The Antennae Galaxies (Figure 10.18) contain over 15 billion solar masses of hydrogen gas and will become a starburst galaxy as their ongoing merger continues to trigger rapid star formation.

A few collisions and mergers could leave a galaxy with no gas and dust from which to make new stars.

ring galaxy A galaxy that resembles a ring around a bright nucleus, resulting from a head-on collision between two galaxies.

starburst galaxy A galaxy undergoing a rapid burst of star formation.

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Image Credit: NASA, ESA, CFHT, CXO, M.J. Jee (University of California, Davis), and A. Mahdavi (San Francisco State University)

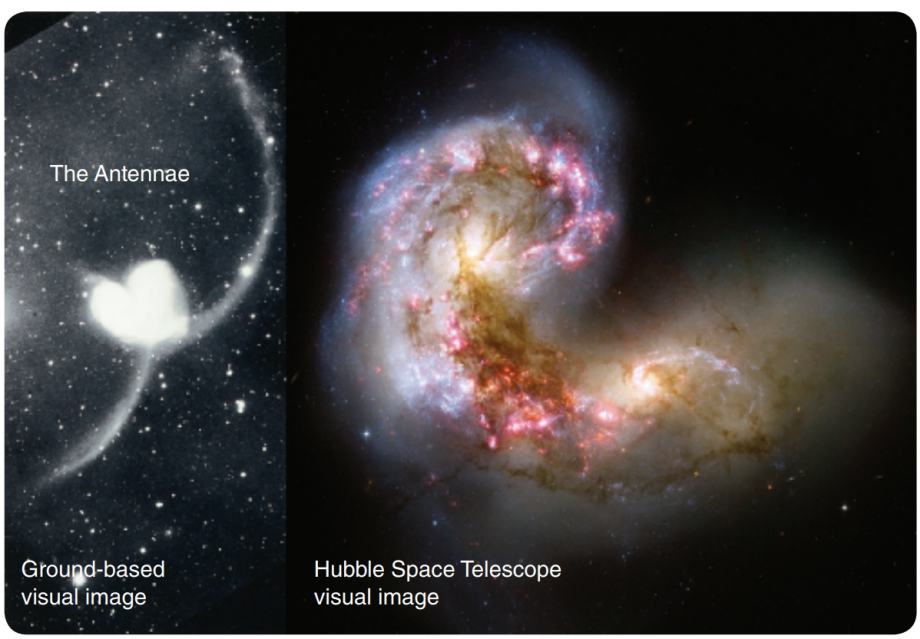
Figure 10.17 Dark matter in merging galaxy cluster Abell 520. This composite image shows the distribution of dark matter, galaxies, and hot gas in the core of the merging galaxy cluster Abell 520, formed from a violent collision of massive galaxy clusters.

Astronomers now suspect that some large ellipticals are formed by the merger of two or more galaxies. The dwarf ellipticals (too small to be formed by mergers) and irregulars may be fragments left over from the merger of larger galaxies.

In contrast, spirals seem never to have suffered major collisions. Their thin disks are delicate and would be destroyed by tidal forces in a collision with a massive galaxy. Also, they retain plenty of gas and dust and continue making stars. Our Milky Way Galaxy has evidently never merged with another large galaxy. However, the Milky Way Galaxy, along with its large spiral neighbour the Andromeda Galaxy, seems to have cannibalized smaller galaxies. The Milky Way Galaxy is currently snacking on the two Magellanic Clouds that orbit around it. Its tides are also pulling apart two other small satellite galaxies, the Sagittarius Galaxy and Canis Major Dwarf Galaxy, producing great streamers of stars wrapped around the Milky Way (see Figure 10.8 and **Visualizing Astronomy 10.1, Galaxy Classification**). Almost certainly, our galaxy has dined on other small galaxies in the past.

Computer simulation derived from measurements of the motion of Andromeda Galaxy, now 2.5 million light-years away, shows the collision course with the Milky Way Galaxy due to the mutual pull of gravity between the two galaxies and the invisible dark matter that surrounds them both. The galaxies will collide in 4 billion years (Figure 10.19), and it will take an additional 2 billion years after the encounter for the interacting galaxies to completely merge under the tug of gravity and reshape into a single elliptical galaxy, similar to the kind commonly seen in the local universe. The galaxies will go through each other, and stars will be thrown into different orbits around the new galactic centre. Simulations show that our solar system will probably be tossed much farther from the galactic core than it is today.

Barred spiral galaxies also may be the product of tidal interactions. Mathematical models show that bars are not stable and should eventually dissipate. It may take tidal interactions with other galaxies to regenerate the bars. Because well over half of all spiral galaxies have bars, you can suspect that these tidal interactions are common. The Milky Way Galaxy is probably a barred spiral (refer to Figure 9.10); its interaction with its two Magellanic Cloud companions or the more distant but very massive Andromeda Galaxy could be the cause.



Brad Whitmore, STScI/ NASA

Figure 10.18 Hubble Space Telescope galaxy images of NGC 4038 and 4039, known as the Antennae Galaxies, reveal that the two galaxies are blazing with star formation. Roughly a thousand massive star clusters have been born. Spectra show that these galaxies are 10 to 20 times richer in elements such as magnesium and silicon than the Milky Way Galaxy. Such metals are produced by massive stars and spread by supernova explosions.

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NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger

Figure 10.19 Collision of the Milky Way and Andromeda galaxies in 3.75 billion years, represented as seen from Earth. The Milky Way will be the same in the sky as it is now, but Andromeda will start to fill the sky.

Other processes can alter galaxies. The S0 galaxies, which have disks and bulges like a spiral galaxy but no spiral arms, may have lost much of their gas and dust while moving through the gas trapped in the dense clusters to which they belong. For example, X-ray observations show that many clusters of galaxies contain thin, hot gas between the galaxies. A galaxy moving through that gas would encounter a tremendous wind that could strip away its gas and dust.

Observations with the largest and most sophisticated telescopes take astronomers back to the age of galaxy formation. At great distances the look-back time is so large that they see the universe as it was soon after the galaxies began to form (Figure 10.13, bottom panel). There were more spirals then and fewer ellipticals. The observations show that galaxies were closer together then; about 33 percent of all distant galaxies are in close pairs, but only 7 percent of nearby (in other words, present-day) galaxies are in pairs. The observational evidence clearly supports the hypothesis that galaxies have evolved by merger.

The evolution of galaxies is not a simple process. A good theory helps you understand how nature works, and astronomers are just beginning to understand the exciting and complex story of the galaxies. Nevertheless, it is already clear that galaxy evolution has some resemblance to a pie-throwing contest and is just about as neat.

In the next section you will encounter a zoo of strange galaxies and unusually energetic sources, which might hide clues about the very early stages in evolution of galaxies. For now, they look like scattered pieces around partially assembled puzzle. It is important to note how scientists, in the best of all mystery stories, carefully examine each piece of the puzzle, its relation to other pieces, and its place in a grand picture of the evolution of matter in the universe.

10.5 Active Galaxies, Quasars, and Supermassive Black Holes

Since the 1940s the detectors of wavelengths of light beyond the visible started changing our view of the universe. The night sky looks different in radio, in X-ray, and in ultraviolet or infrared light. Astronomers have discovered numerous unusually energetic galaxies and centres of galaxies. Many were found to be at large redshifts, which would mean at large distances from us, and because of look-back time they are earlier in the history of galaxies. The story of the birth and youth of galaxies is still unclear, riddled with hypotheses, and numerous seemingly unrelated objects with exotic names—quasars, blazars, Seyfert galaxies, AGNs, and supermassive black holes, to name a few. Better telescope resolution enabled astronomers to reveal that several of these objects could, in fact, be connected—and a few could simply be different views of the same object depending on the direction in which they are observed, as you will study in the search for a unified model later in Figure 10.26.

Active Galaxies

Galaxies that were stronger-than-usual emitters of electromagnetic radiation were classified into various categories of **active galaxies**. Today, evidence points to a possible common origin of bursting activity in most types of active galaxies—interaction of galaxies and activity in the very centres of galaxies, which are referred to as **active galactic nuclei (AGN)**. By looking far away and back in time, astronomers have discovered that the origin of energy sources and outbursts in active galaxies is closely related to the formation and history of galaxies.

Doppler shift measurements show that the stars and gas are orbiting very rapidly near the centres of many galaxies, both spiral (Figure 10.20) and elliptical (Figure 10.21). To hold stars and gas in such small, short-period orbits, the centres of those galaxies must contain

active galaxy A galaxy whose centre emits large amounts of excess energy, often in the form of radio emissions. Active galaxies have massive black holes in their centres into which matter is flowing.

active galactic nuclei (AGN) The centres of active galaxies that are emitting large amounts of excess energy.

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ALMA (ESO/NAOJ/NRAO), Imanishi et al., NASA/ESA Hubble Space Telescope and A. van der Hoeven.

Figure 10.20 The central region of the spiral galaxy M77. The ALMA radio telescope revealed the distribution of gas in the very centre of the galaxy—a horseshoe-like structure with a radius of 700 light-years and a central compact component with a radius of 20 light-years. The latter is the gaseous torus around the AGN.

masses of millions to a few billion solar masses, concentrated in a very small diameter, yet no object is visible. The evidence—the absence of any visible object and detection of a specific type of radiation—seems to require that the nuclei of many galaxies contain supermassive black holes. Recall from Chapter 9 that the Milky Way Galaxy contains a supermassive black hole at its centre. That is typical of galaxies. However, it is a common misconception that the orbits of stars throughout a galaxy are controlled by the central black hole. The masses of those black holes, large as they may seem, are negligible compared with a galaxy's mass. The 4.3-million-solar-mass black hole at the centre of the Milky Way Galaxy contains only a thousandth of 1 percent of the total mass of our galaxy.

radio galaxy A galaxy that is a strong source of radio signals.

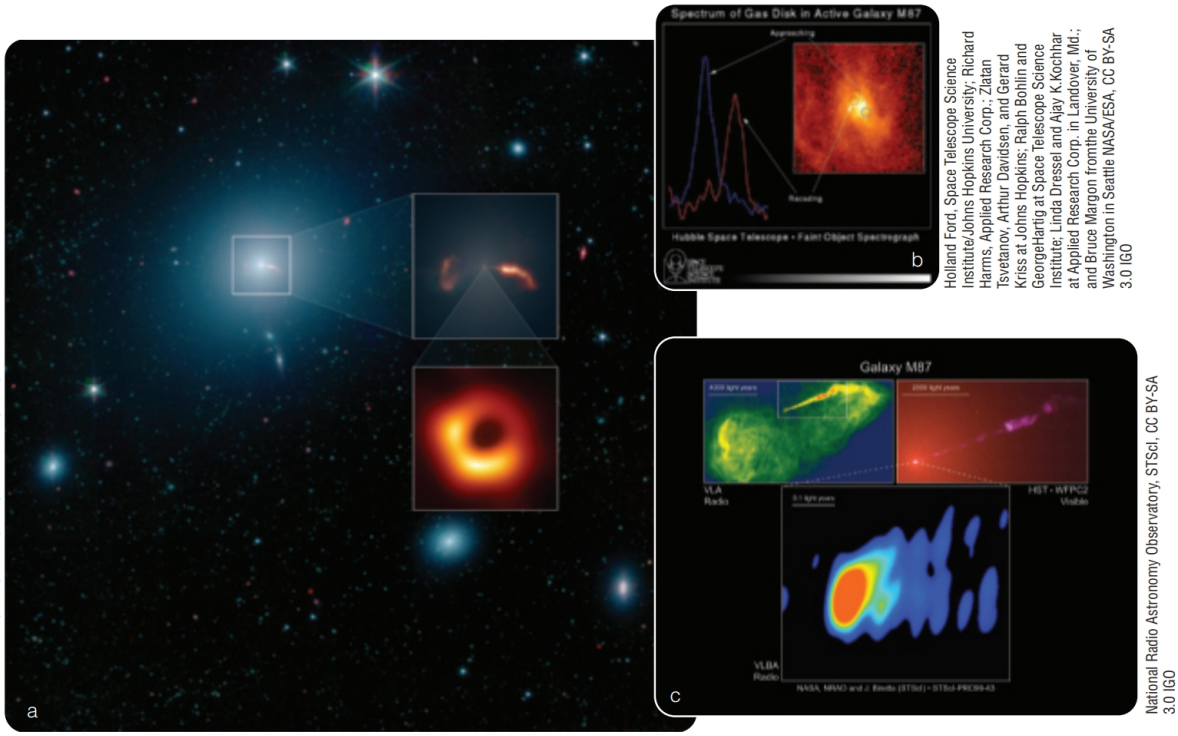
Seyfert galaxy An otherwise normal spiral galaxy with an unusually bright, small core that fluctuates in brightness.

Galaxies that are violent emitters of radio waves are called **radio galaxies**. It seems like the activity that causes radio emission is associated with interaction of a galaxy and an active nucleus. AGN, most probably supermassive black hole, is emitting powerful jets of radio waves perpendicular to the galactic disk. The spectrum of radio waves is characteristic for synchrotron radiation (see Chapter 8), electron emission when electrons from hot ionized gas shoot from the core spiral, with almost the speed of light, along magnetic field lines, ionizing the surrounding gas (Figure 10.22). This could be the source of gas lobes that emit radio waves (Figures 10.21c and 10.25).

The same reason could be behind the activity of spiral active galaxies called **Seyfert galaxies**, whose nuclei, despite their small size not much bigger than Earth's orbit, emit a hundred times more energy than the entire Milky Way Galaxy.

Seyfert nuclei are three times more common in interacting pairs of galaxies than in isolated galaxies (see **How Do We Know? 10.3**). Also, about 25 percent of Seyfert galaxies have peculiar shapes, suggesting tidal interactions with other galaxies. This statistical evidence hints that Seyfert galaxies may have been triggered into activity by collisions or interactions with companions. Some Seyferts are observed to be expelling

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NASA/JPL-Caltech/IPAC/Event Horizon Telescope Collaboration (bottom inset) Photo by National Science Foundation via Getty Images/Getty Images News/Getty Images

Holland Ford, Space Telescope Science Institute/Johns Hopkins University; Richard Harms, Applied Research Corp.; Zlatan Tsvetanov, Arthur Davidsen, and Gerard Kriss at Johns Hopkins; Ralph Bohlin and GeorgeHartig at Space Telescope Science Institute; Linda Dressel and Ajay K.Kochhar at Applied Research Corp. in Landover, Md.; and Bruce Margon fromthe University of Washington in Seattle NASA/ESA, CC BY-SA 3.0 IGO

National Radio Astronomy Observatory, STScI, CC BY-SA 3.0 IGO

Figure 10.21 (a) Over 120 000 light-years in diameter, elliptical galaxy M87 (NGC 4486) is the dominant galaxy at the centre of the Virgo Galaxy Cluster, some 55 million light-years away. Spitzer infrared telescope shows a trace of a jet of material spewing to the right of the galaxy—a feature that was previously one key indicator that a supermassive black hole lived at the galaxy's center. Analysis of images from EHT (Figure 4.11 c), produced this first direct image of a black hole. A bright ring formed as light bends in the intense gravity around a black hole that is 6.5 billion times more massive than the Sun. (b) The Doppler shift shows that the gas orbits the centre of a giant elliptical active galaxy M87 so fast that a very massive object must be in a very small nucleus. The measurement was made by studying how the light from the disk is redshifted and blueshifted as part of the swirling disk spins in Earth's direction and the other side spins away from Earth. (c) Radio (top left) and optical (top right) images of the centre of M87 show a region near a supermassive black hole. A powerful beam, or jet, of subatomic particles is spewing outward at nearly the speed of light, straight for thousands of light-years.

matter in oppositely directed jets, a geometry you have seen on smaller scales when matter flows into neutron stars and black holes and forms an accretion disk with jets (Figure 10.22).

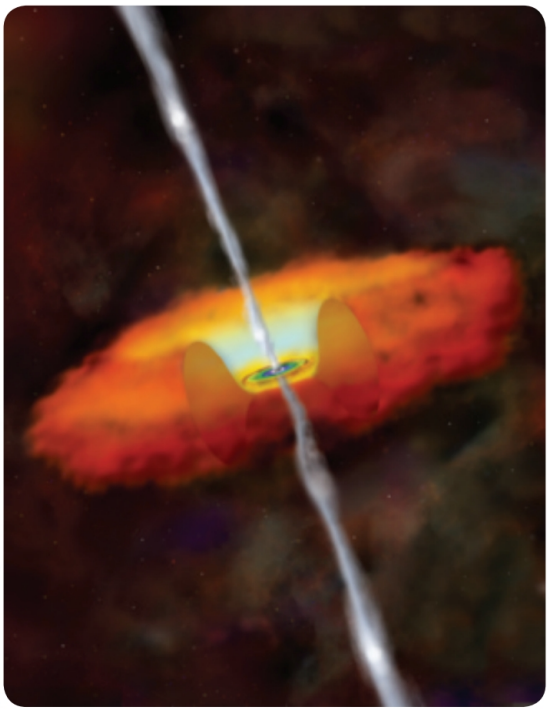
Theoretical predictions and observational evidence lead astronomers to conclude that the core of a Seyfert galaxy contains a supermassive black hole with a mass as high as a billion solar masses, like in M77 (Figure 10.20). Gas in the centres of Seyfert galaxies is travelling so fast it would escape from a normal galaxy, and only large central masses could exert enough gravity to hold the gas inside the nuclei. Encounters with other galaxies could throw matter toward the black hole, and lots of energy can be liberated by matter flowing through an accretion disk into a black hole.

If you are wondering where these supermassive black holes in the nuclei of galaxies came from, that question is linked to a second question: What makes a supermassive black hole erupt? Answering these two questions will help you understand how galaxies form.

Evidence is accumulating that most galaxies contain a supermassive black hole at their centre (Figure 10.23). Only a few percent of galaxies, however, have obviously active galactic nuclei. Most of the supermassive black holes are dormant. Presumably they are not being fed large amounts of matter. A slow trickle of matter flowing into the supermassive black hole at the centre of our galaxy could explain the relatively mild activity seen there. It would take a larger meal to trigger an eruption such as those seen in active galactic nuclei.

What could trigger a supermassive black hole to erupt? The answer—tides—is something you studied in Chapter 3. As you have learned, tides twist interacting galaxies and rip matter away into tidal tails. Active galaxies

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(a) NASA/Chandra X-ray Observatory/M. Weiss, (b) NASA

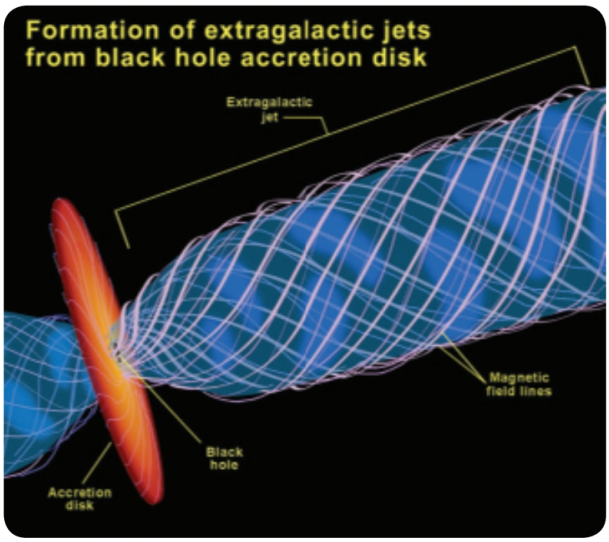
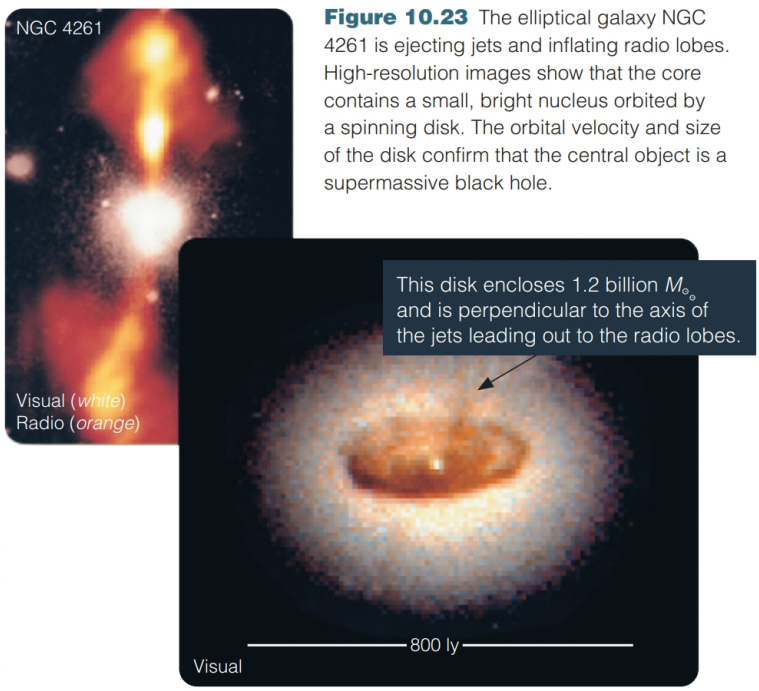


Figure 10.22 (a) An artist's conception shows a black hole surrounded by a disk of hot gas and a large torus of cooler gas and dust, and jets of high-energy particles that are propelled away from the vicinity of the black hole by intense electric and magnetic fields. (b) A jet of energy being shot out in opposite directions from a black hole located in the centre (nucleus) of a galaxy. The black hole is gravitationally pulling in material from a flattened accretion disk of matter. The jets form probably due to violent twisting of magnetic field lines (represented as white spirals in the image) caused by superheated material swirling into the black hole.



L. Ferrarese (John Hopkins University) and Nasa, Walter Jaffe/Leiden Observatory, Holland Ford/JHU/STScI

Figure 10.23 The elliptical galaxy NGC 4261 is ejecting jets and inflating radio lobes. High-resolution images show that the core contains a small, bright nucleus orbited by a spinning disk. The orbital velocity and size of the disk confirm that the central object is a supermassive black hole.

are often distorted. Mathematical models show that those interactions can also throw stars and clouds of interstellar gas and dust inward toward the galaxies' centres. A sudden flood of matter flowing into a supermassive black hole would trigger it into eruption. A steady diet of inflowing gas, dust, and an occasional star would keep the supermassive black hole in an AGN active.

A few dozen supermassive black holes have measured masses, and their masses are correlated with the masses of the host galaxies' central bulges. In each case, the mass of the black hole is about 0.5 percent the mass of the surrounding central bulge. It is possible that, as a galaxy forms its central bulge, a certain fraction of the mass sinks to the centre, where it forms a supermassive black hole. All of that matter flowing together to form the black hole would release a tremendous amount of energy and trigger a violent eruption. Long ago, when galaxies were actively forming, the birth of the central

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HOW DO WE KNOW? 10.3



Statistical Evidence

How can statistics be useful if they can't be specific? Some scientific evidence is statistical. Observations suggest, for example, that Seyfert galaxies are more likely to be interacting with a nearby companion than a normal galaxy is. This is statistical evidence, so you can't be certain that any specific Seyfert galaxy will have a companion. How can scientists use statistical evidence to learn about nature when statistics contain built-in uncertainty?

Meteorologists use statistics to determine how frequently hurricanes of a certain size are likely to occur. Small storms happen every year, but big storms may happen on average only every ten years. Hundred-year hurricanes are much more powerful but occur much less frequently: on average only once in a hundred years.

Those meteorological statistics can help you make informed decisions—as long as you understand the powers and limitations of statistics. Would you buy a house protected from a river by a levee that was not designed to withstand a hundred-year storm? In any one year, the chance of your house being destroyed would be only 1 in 100. You know the storm will hit eventually, but you don't know when. If you buy the house, a storm might destroy the levee the next year, but you might own the house for your whole life and never see a hundred-year storm. The statistics can't tell you anything about a specific year.

Before you buy that house, there is an important question you should ask the meteorologists: "How much data do you have on storms?" If they have only ten years of data they don't really know much about hundred-year storms. If they have three centuries of data their statistical data are significant.

Sometimes people dismiss important warnings by saying, "Oh, that's only statistics." Scientists can use statistical evidence if it passes two tests. It cannot be used to draw conclusions about specific cases, and it must be based on large enough data samples so the statistics are significant. With these restrictions, statistical evidence can be a powerful scientific tool.



© Marko Georgiev/Getty Images

Statistics can tell you that a bad storm will eventually hit, but it can't tell you when.

bulges must have triggered many AGN. Later episodes of AGN activity could be triggered by interactions or mergers with other galaxies.

Quasars

The largest telescopes detect multitudes of faint points of light with peculiar emission spectra; these are objects called **quasars** (also known as *quasi-stellar objects*, or *QSOs*). Although astronomers now recognize quasars as extreme examples of AGN as well as some of the most distant visible objects in the universe, they were a mystery when they were first identified.

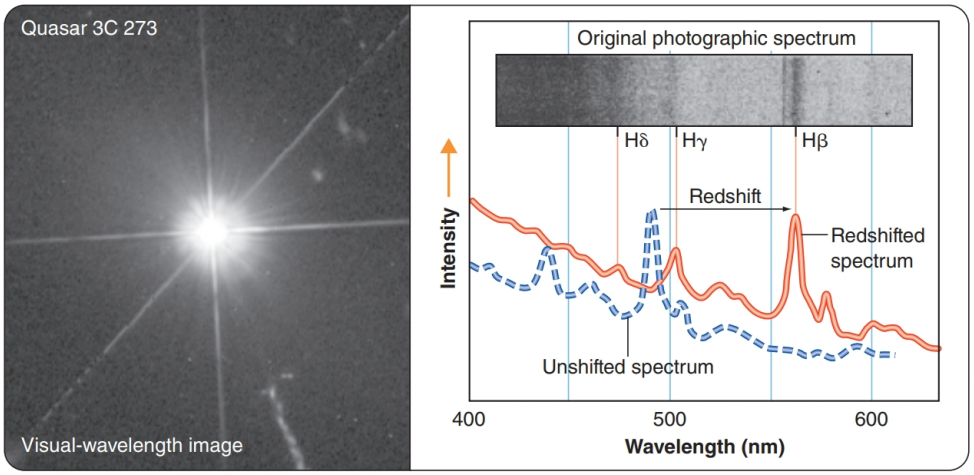
In the early 1960s, photographs of the location of some radio sources that resembled radio galaxies revealed only single starlike points of light. The first of these objects identified was 3C 48, and later the source 3C 273 was found. They were obviously not normal radio galaxies. Even the most distant photographable galaxies look fuzzy, but these objects looked like stars. Their spectra, however, were not like stellar spectra, so the objects were called quasi-stellar objects.

For years, the spectra of quasars were a mystery. A few unidentifiable emission lines were superimposed on a continuous spectrum. In 1963, astronomer Maarten Schmidt calculated that if hydrogen Balmer lines were redshifted by $z = 0.158$, meaning each line's change in wavelength divided by its lab wavelength equals 0.158 (see **The Doppler Formula** and **The Hubble Law** in the Math Reference Cards), they would fit the observed lines in 3C 273's spectrum (Figure 10.24). Other quasar spectra quickly yielded to this type of analysis, revealing even larger redshifts.

To understand the significance of these large redshifts and the large velocities

quasar Small, powerful source of energy in the active core of a very distant galaxy.

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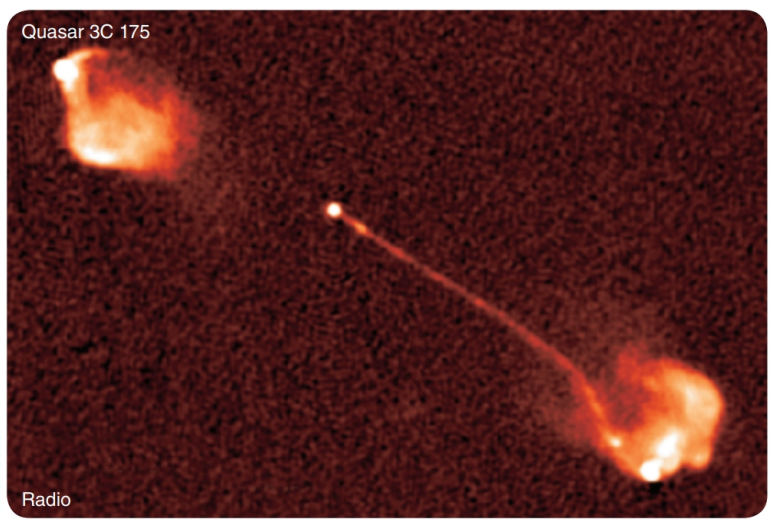
Figure 10.24 This image of 3C 273 (left) shows the bright quasar at the centre surrounded by faint fuzz. Note the jet protruding to lower right. The spectrum of 3C 273 (right, top) contains three hydrogen Balmer lines redshifted by 15.8 percent. The dotted line shows the unshifted positions of the spectrum.

of recession they imply, recall the Hubble law from earlier in this chapter, which states that galaxies have apparent velocities of recession proportional to their distances. (Refer to **The Hubble Law** in the Math Reference Cards.) The large redshifts of the quasars imply that they must be at great distances, some farther away than any known galaxy. Many quasars are evidently so far away that galaxies at those distances are very difficult to detect, yet the quasars are easily photographed. This leads to the conclusion that quasars must be ultraluminous, 10 to 1000 times the luminosity of a large galaxy.

Soon after quasars were discovered, astronomers detected fluctuations in their brightness over time scales of hours or minutes. The rapid fluctuations in quasars showed that they are small objects like AGN, only a few light-minutes or light-hours in diameter. Evidence such as that seen in Figure 10.25 has accumulated to suggest that quasars are the most luminous AGN and are located in the centres of galaxies.

In the next chapter, you will see evidence that the universe began 13.8 billion years ago. Some quasars are over 10 billion light-years away, and because of their large look-back times they appear as they were when the universe was only 10 percent of its present age. Evidently, quasars are embedded in distant galaxies. Perhaps we can assume that distant quasars seen when the universe was just 4 billion years old are located in the ancestors of galaxies. The Hubble Space Telescope observation of quasars in elliptical galaxies reveals the existence of early galaxies that are bluer than nearby elliptical galaxies. This could imply that we are seeing elliptical galaxies in formation. The first clouds of gas that formed galaxies would have also made supermassive black holes at the centres of those galaxies' central bulges. The abundance of matter flooding into those early black holes could have triggered outbursts that are seen as quasars.

Note that galaxies were closer together when the universe was young and had not expanded very much. Because they were closer together, the forming galaxies collided more often, and these collisions between galaxies could throw matter into central supermassive black holes and trigger eruptions. Quasars are often located in host galaxies that are distorted as if they were interacting with other galaxies.



NRAO/AUI/NSF

Figure 10.25 This radio image of quasar 3C 175 reveals the quasar is ejecting a jet, and it is flanked by radio lobes. Presumably you see only one jet because it is directed approximately toward Earth, and the other jet is invisible because it is directed away from Earth. The presence of jets and radio lobes indicates that quasars are the active cores of distant galaxies.

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Quasars are most common with redshifts a little over 2 and less common with redshifts above 2.7. The largest quasar redshifts are over 6, but such high-redshift quasars are quite rare. If you looked at quasars with redshifts a bit over 2, you would be looking back to an age when galaxies were actively forming, colliding, and merging. In that era, quasars were about 1000 times more common than they are now. Even so, only a fraction of galaxies had quasars erupting in their cores at any one time. If you look back to higher redshifts, you would see fewer quasars because you would be looking back to an age when the universe was so young it had not yet begun to form many galaxies and quasars.

Then where are all the dead quasars? There is no way to get rid of supermassive black holes. Astronomers have discovered that nearly all galaxies contain supermassive black holes, and those black holes may have suffered quasar eruptions when the universe was younger, galaxies were closer together, and infalling gas and dust were more plentiful. Quasar eruptions became less common as galaxies became more stable and as the abundance of gas and dust in the centres of galaxies was exhausted. The Milky Way Galaxy is a good example. It could have been a quasar long ago, but today its supermassive black hole is resting. Dormant black holes at the centres of galaxies today can be reawakened to become AGN by galaxy collisions and interactions.

The Search for a Unified Model

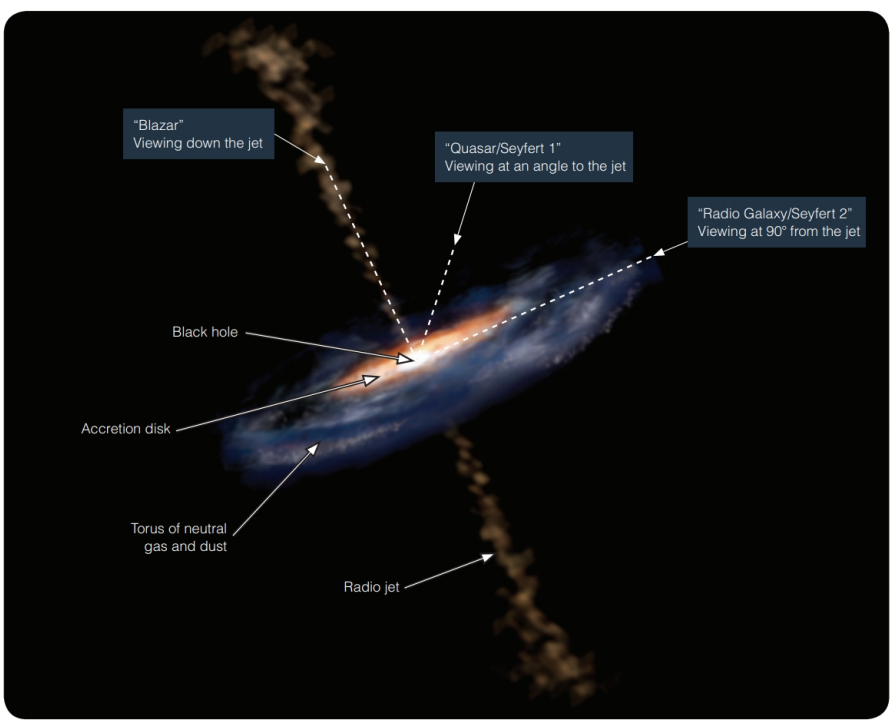
unified model An attempt to explain the different types of active galactic nuclei using a single model viewed from different directions.

Astronomers studying galaxies are now developing a **unified model** of AGN and quasars. A monster black hole is the centrepiece (Figure 10.26).

Even a supermassive black hole is quite small compared with a galaxy. A 10-million-solar-mass black hole would be only one-fifth the diameter of Earth's orbit. The matter in an accretion disk can get very close to the black hole, orbit very fast, and grow very hot. Theoretical calculations indicate that the disk immediately around the black hole is "puffed up," thick enough to hide the central black hole from some viewing angles. The hot inner disk seems to be the source of the jets often seen coming out of active galaxy cores, but astronomers don't yet understand the process by which these jets are generated. Mathematical models indicate that the outer part of the disk is a fat, relatively cold torus (doughnut shape) of dusty gas.

According to the unified model depicted in Figure 10.26, when you view the core of an AGN or QSO what you see depends on how its accretion disk is tipped with respect to your line of sight.

1. If you view the accretion disk from the edge, you cannot see the central zone at all because the thick dusty torus



NASA E/PO, Sonoma State University, Aurore Simonnet

Figure 10.26 This illustration shows the different features of an active galactic nucleus (AGN), and how our viewing angle determines what type of AGN we observe. The extreme luminosity of an AGN is powered by a supermassive black hole at the centre.

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blocks your view. Instead, you see radiation emitted by gas lying above and below the central disk, which is therefore relatively cool and moving relatively slowly, with small Doppler shifts. Thus, you see narrower spectral lines coming from what is called the narrow-line region. You see it as a radio Seyfert galaxy.

2. If the accretion disk is tipped slightly, you may be able to see some of the intensely hot gas in the central cavity. This is called the broad-line region because the gas is hot and also orbiting at high velocities. The resulting high Doppler shifts spread out the spectral lines. It looks like what we call a quasar.
3. If you look directly into the central cavity around the black hole—down the dragon's throat, so to speak—you see the jet emerging perpendicular to the accretion disk and coming straight at you. Model calculations indicate this would result in a very luminous and highly variable source with few or no emission lines, only continuous synchrotron emission. This is the appearance of AGN known as **blazars** (BL lacerate objects).

blazar A type of active galaxy nucleus that is especially variable and has few or no spectral emission lines.

Astronomers are now using this unified model to sort out the different kinds of active galaxies and quasars so they can understand how they are related. For example, about 1 percent of quasars are strong radio sources, and the radio radiation may come from synchrotron radiation (see Chapter 8) produced in the high-energy gas and magnetic fields in the jets. Another example: Infrared observations through dust revealed that cores of some radio galaxies harbour objects much like quasars. Astronomers have begun to refer to such hidden objects as "buried quasars."

The unified model is far from complete. The detailed structure of accretion disks is poorly understood, as is the process by which the disks produce jets. Furthermore, the spiral Seyfert galaxies are clearly different from the giant elliptical galaxies that have double radio lobes. Unification does not explain all of the differences among active galaxies. Rather, it is a model that provides some clues to what is happening in AGN and quasars.

The **Big Picture**

You are riding a small planet orbiting a humdrum star that is just one of at least 100 billion in the Milky Way Galaxy. You have just learned that there are at least 100 billion galaxies visible with existing telescopes, and that each of these galaxies contains roughly 100 billion stars. Humans fight wars over politics, religion, and economics; we do our work, play our games, and wash our laundry. It's all important stuff, but next time you are frantically rushing to a meeting, glance up at the sky.

When you look at galaxies, you are looking across voids deeper than human imagination. You can express such distances with numbers, but the distance is truly beyond human comprehension. Some people say astronomy makes them feel humble, but before you agree, consider how you can feel small without feeling humble. We humans live out our little lives on our little planet, but we are figuring out some of the biggest mysteries of the universe. We are exploring deep space and deep time and coming to understand what galaxies are and how they evolve. Most of all, we are beginning to understand what we are. That's something to be proud of.

Review and **Discussion Questions**

Review Questions

1. What types of galaxies exist?
2. How do astronomers measure the distances to galaxies, and how does that allow the sizes, luminosities, and masses of galaxies to be determined?
3. Why are there different kinds of galaxies, and how do galaxies evolve?
4. How are galaxies distributed in the universe?
5. What is the energy source for active galaxies, what can trigger the activity, and what does that reveal about the history of galaxies?

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6. How do long-exposure photos of two selected areas of the sky reveal that galaxies are very common?
7. What is the difference between an Sa and an Sb galaxy? Between an S0 and an Sa galaxy? Between an Sb and an SBb galaxy? Between an E7 and an S0 galaxy?
8. Explain how the rotation curve method of finding a galaxy's mass is similar to the method used to find the masses of binary stars.
9. What is the difference between rich and poor clusters of galaxies?
10. What holds clusters of galaxies together?
11. Does the Milky Way belong to a rich or poor cluster of galaxies?
12. What is the evidence for the existence of dark matter in galaxies?
13. What is the evidence for the existence of dark matter in clusters of galaxies?
14. Why are spiral galaxies good standard candles?
15. Explain how the Hubble law allows you to estimate the distances to galaxies.
16. How can collisions affect the shapes of galaxies?
17. What evidence can you cite that galactic cannibalism really happens?
18. What evidence suggests that Seyfert galaxies have suffered recent interactions with other galaxies?
19. What is the source of radio waves emitted by a jet from the vicinity of a black hole?
20. What is the evidence for the existence of supermassive black holes in galaxies?
21. What evidence shows that quasars are ultraluminous but must be small?
22. What evidence is there that quasars occur in distant galaxies?
23. **How Do We Know?** Classification helped Darwin understand how creatures evolve. Has classification helped you understand how galaxies evolve?
24. **How Do We Know?** How would you respond to someone who said, "Oh, that's only statistics"?

Discussion Questions

1. From what you know about star formation and the evolution of galaxies, do you think irregular galaxies should be bright or faint in the infrared relative to visible wavelengths? Why did you make this choice? What about starburst galaxies? What about elliptical galaxies?
2. What are the similarities between various types of active galaxies?
3. Even though the central black hole is a tiny portion of a mass of a galaxy, how can it contribute to an intense energy output of active galaxy?
4. How are radio galaxies, quasars, and blazars connected in the unified model of galaxies?
5. Do you think that our galaxy is currently an active galaxy? Do you think it ever was in the past? Could it have hosted a quasar when it was young?

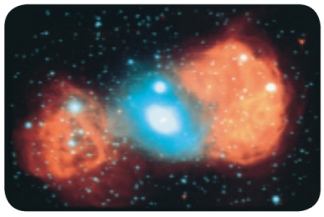
Learning to Look

1. In the image below you see two interacting galaxies; one is nearly face-on and the other is nearly edge-on. Discuss the shapes of these galaxies and describe what is happening.



NASA, ESA, and the Hubble Heritage Team (STScI/AURA)

2. The image at right combines visual (blue) with radio (red) to show the galaxy radio astronomers call Fornax A. Explain the features of this image. Is it significant that the object is a distorted elliptical galaxy in a cluster?



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STUDY TOOLS

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- Tear Out the Review Card on Galaxies.

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PART THREE

11 Cosmology in the 21st Century

CHAPTER OUTLINE

11.1 Introduction to the Universe
11.2 The Big Bang Theory
11.3 Space and Time, Matter and Energy
11.4 Modern Cosmology

GUIDEPOST

Beginning with Chapter 1, you have been on an outward journey through the universe. At this point, you have reached the limit of your travels in space and time and can contemplate the universe as a whole. The ideas in this chapter are among the biggest and most difficult in all of science. Can you imagine a limitless universe, or the first instant of time?

As you explore this chapter, you will find answers to three important questions:

- Does the universe have a centre and an edge?
- What is the evidence that the universe began with a big bang?
- How has the universe evolved, and what will be its fate?

When you finish studying this chapter, you will have a modern insight into the nature of the universe, as well as where you are and what you are.

Look at your thumb. The matter in your thumb was present in the fiery beginning of the universe. **Cosmology**, the study of the universe as a whole, can tell you where your body's matter comes from, and it can tell you where that matter is going. Cosmology is a mind-bending, weird subject, and you can enjoy it for its strange ideas. It is fun to think about space-time stretching like a rubber sheet, invisible energy pushing the universe to expand faster

cosmology The study of the nature, origin, and evolution of the universe.



Dmitriy Rybin/Shutterstock.com

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The big bang. Conceptual computer artwork of the origin and evolution of the universe. The term big bang describes the beginning of expansion of the universe as we know it 13.8 billion years ago. The initial conditions are not known, but less than a second after the beginning, temperatures were trillions of degrees Celsius, and the primordial universe was much smaller than an atom. It has been expanding and cooling ever since

Mankind has made giant steps forward. However, what we know is really very, very little compared to what we still have to know.

Fabiola Gianotti,
physicist and leader of the ATLAS experiment that discovered the Higgs boson

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and faster, and the origin of vast walls of galaxy clusters. Notice that this is better than speculation—it is all supported by evidence. Cosmology, however strange it may seem, is a serious and logical attempt to understand how the universe works, and it leads to wonderful insights into how we came to be a part of it.

11.1 Introduction to the Universe

Many people have an impression of the universe as a vast sphere filled with stars and galaxies. However, as you begin exploring the universe, you need to become aware of your assumptions so they do not mislead you. The first step is to deal with an expectation so obvious that most people, for the sake of a quiet life, don't even think about it.

The Edge–Centre Problem

In your daily life, you are accustomed to boundaries. Rooms have walls, athletic fields have boundary lines, countries have borders, and oceans have shores. It is natural to think of the universe as having an edge, but that idea can't be right.

If the universe had an edge, imagine going to the edge. What would you find there: A wall? A great empty space? Nothing? Even a child can ask, if there is an edge to space, what's beyond it? A true edge would have to be more than just an end of the distribution of matter, it would have to be an end of space itself; but then, what would happen if you tried to reach past or move past that edge?

Modern observations indicate that the universe could be infinite and have no edge. Note that you find the centres of things—galaxies, globular clusters, oceans, pizzas—by referring to their edges. If the universe has no edge, it cannot have a centre.

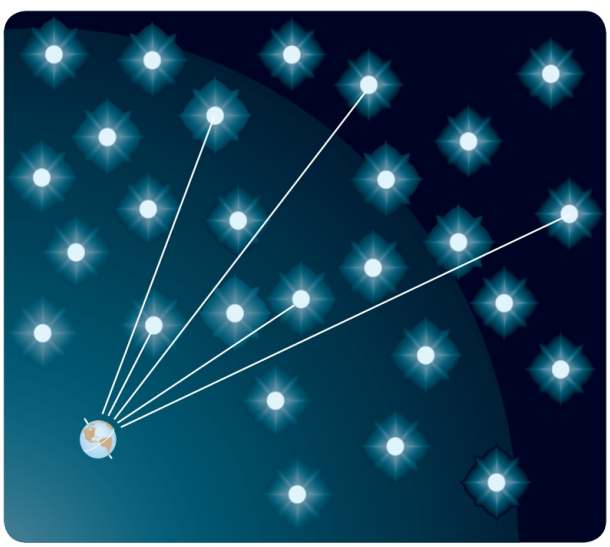
It is a common misconception to imagine that the universe has a centre, but, as you have just learned, that is impossible. As you study cosmology, you need to take care to avoid thinking that there is a centre of the universe.

Olbers's paradox The conflict between theory and evidence regarding the darkness of the night sky.

The Necessity of a Beginning

The simple observation that the night sky is dark is an important one. This is because reasonable assumptions about the universe can lead us to conclude that the night sky would actually glow blindingly bright! This conflict between observation and theory is called **Olbers's paradox**, after Heinrich Olbers, an Austrian physician and astronomer who publicized the problem in 1826; in fact, *problem* or *question* would be more accurate words than *paradox*. Olbers was not the first to pose the question, but it is named after him because modern cosmologists were not aware of the earlier discussions. After revising your assumptions about the universe, you will be able to answer Olbers's question and understand why the night sky is dark.

The point Olbers made seems simple. Suppose you assume that the universe is infinite and filled with stars. (The clumping of stars into galaxies can be shown mathematically to make no difference.) If you look in any direction, your line of sight must eventually reach the surface of a star (see Figure 11.1). Now think about trying to see out of a forest. When you are deep in a forest, every line of sight ends on a tree trunk, and you cannot see out of the forest. By analogy, every line of sight from Earth out into space should eventually end on the surface of a star, so the entire sky should be as bright as the surface of an average star—like suns crowded "shoulder to shoulder," covering the sky from horizon to horizon. It should not get dark at night.



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Figure 11.1 Olbers's paradox. If the universe is infinite and filled with stars any line from Earth should eventually reach the surface of a star. This assumption predicts that the night sky should glow as brightly as the surface of the average star.

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Today, cosmologists believe they understand why the sky is dark. The universe is not eternal—that is, not infinitely old. That answer to Olbers's question was suggested by Edgar Allan Poe in 1848. He proposed that the night sky is dark because the universe is not infinitely old but instead began at some time in the past. The more distant stars are so far away that light from them has not yet reached Earth. That is, if you look far enough, the look-back time is greater than the age of the universe. The night sky is dark because the universe had a beginning.

This is a powerful idea because it clearly illustrates the difference between the universe and the observable universe. The universe is everything that exists, but the **observable universe** is the part that you can see. As you have learned, astronomers now know the universe is 13.8 billion years old. Because of that, the observable universe is limited by a light travel time of 13.8 billion years.

Cosmic Expansion

In 1929, Edwin P. Hubble published his discovery that the sizes of galaxy redshifts are proportional to galaxy distances (refer to Figure 10.4, page 232). Nearby galaxies have small redshifts, but more distant galaxies have larger redshifts. These redshifts imply that the galaxies are receding from each other. Figure 11.2 shows spectra of galaxies in clusters at various distances. The Virgo cluster is relatively nearby, and its redshift is small. The Hydra cluster is very distant, and its redshift is so large that the two dark lines formed by ionized calcium are shifted from near-ultraviolet wavelengths well into the visible part of the spectrum.

The expansion of the universe does not imply that Earth is at the centre. To see why, think about raisin bread. As the dough rises, it pushes the raisins away from each other uniformly at speeds that are proportional to their distances from each other (see Figure 11.3). Two raisins that were originally close are pushed apart slowly, but two raisins that were far apart, having more dough between them, are pushed apart faster. If bacterial astronomers lived on a raisin in your raisin bread, they could observe the redshifts of the other raisins and derive a bacterial Hubble law. They would conclude that their universe was expanding uniformly. It does not matter which raisin the bacterial astronomers lived on, they would get the same Hubble law; no raisin has a special viewpoint. Similarly, astronomers in any galaxy will see the same law of expansion—no galaxy has a special viewpoint.

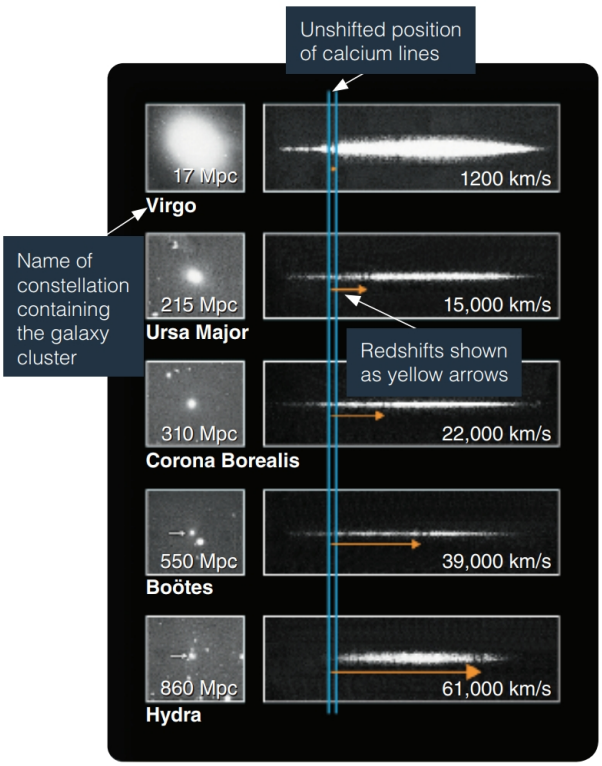


Figure 11.2 These galaxy spectra extend from the near-ultraviolet at left to the blue part of the visible spectrum at right. The two dark absorption lines of once-ionized calcium are prominent in the near-ultraviolet. The redshifts in galaxy spectra are expressed here as apparent velocities of recession. Note that the apparent velocity of recession is proportional to distance.

observable universe The part of the universe that you can see from your location in space and in time.

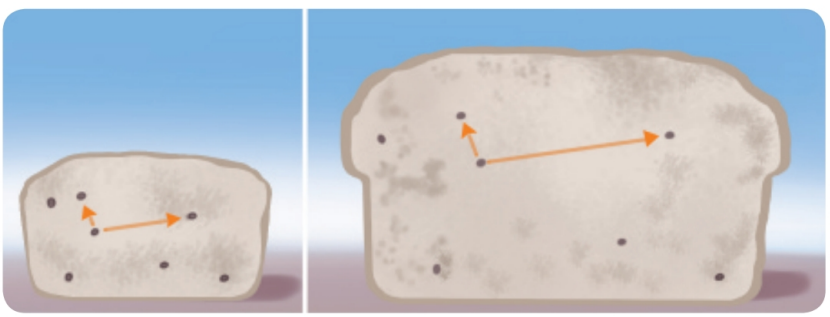


Figure 11.3 An illustration of the raisin bread analogy for the expansion of the universe. As the dough rises, raisins are pushed apart with velocities proportional to distance.

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The raisin bread analogy for the expanding universe no longer works when you consider the crust—the edge—of the bread. Remember that the universe cannot have an edge or a centre, so there can be no centre to the expansion.

11.2 The Big Bang Theory

The expansion of the universe led astronomers to conclude that the universe must have begun with an event of astounding cosmic intensity.

Necessity of the Big Bang

Imagine that you have a video of the expanding universe, and you run it backward. You would see the galaxies moving toward each other. There is no centre to the expansion of the universe, so you would not see galaxies approaching a single spot. Rather, you would see the space between galaxies disappearing, distances between all galaxies decreasing without the galaxies themselves moving, and eventually galaxies beginning to merge. If you ran your video far enough back, you would see the matter and energy of the universe compressed into a high-density, high-temperature state. You can conclude that the expanding universe began with expansion from that condition of extremely high density and temperature, which modern astronomers call the **big bang**.

How long ago did the universe begin? You can estimate the age of the universe with a simple calculation. If you must drive to a city 100 km away and you can travel 50 km/hr, divide distance by speed of travel to learn the travel time: in this example, two hours. To find the age of the universe, divide the distance between galaxies by the speed with which they are separating, and find out how much time was required for them to have reached their present separation. You will fine-tune your estimate later in this chapter, but for the moment you can conclude that basic observations of the recession of the galaxies require that the universe began with a big bang approximately 14 billion years ago. That estimated span is called the **Hubble time**. (Refer to **The Age of the Universe** in the Math Reference Cards.)

big bang The high-density, high-temperature state from which the expanding universe of galaxies began.

Hubble time The age of the universe, equivalent to 1 divided by the Hubble constant. The Hubble time is the age of the universe based on its expansion at a constant rate since the big bang.

Your instinct is to think of the big bang as a historical event, like John Cabot's arrival in what is now Newfoundland: something that happened long ago and can no longer be observed. But the look-back time makes it possible to observe the big bang directly. The look-back time to nearby galaxies is only a few million years, but the look-back time to more distant galaxies is a large fraction of the age of the universe (see Chapter 10). If you looked between and beyond the distant galaxies, back to the time of the big bang, you should be able to detect the hot gas that filled the universe long ago.

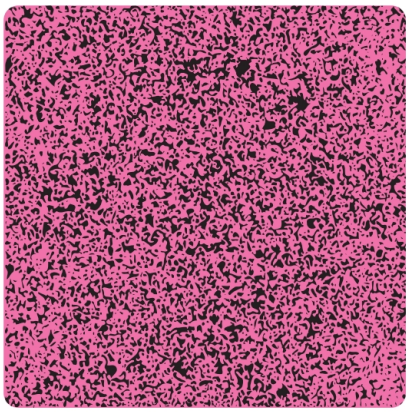
Again, do not think of an edge or a centre when you think of the big bang. It is a very common misconception that the big bang was an explosion and that the galaxies are flying away from a centre. Although your imagination may try to visualize the big bang as a localized event, you must keep firmly in mind that the big bang did not occur at a single place; rather, it filled the entire volume of the universe. We cannot point to any particular place and say, "The big bang occurred over there." The hot, dense state at the instant of the big bang occurred everywhere, and that includes right where you are now. The matter of which you are made was part of the big bang, so you are inside the remains of that event, and the universe continues to expand around you. In whatever direction astronomers look, at great distances they can see back to the age when the universe was filled with dense, hot gas (Figure 11.4).

Evidence for the Big Bang: The Cosmic Microwave Background

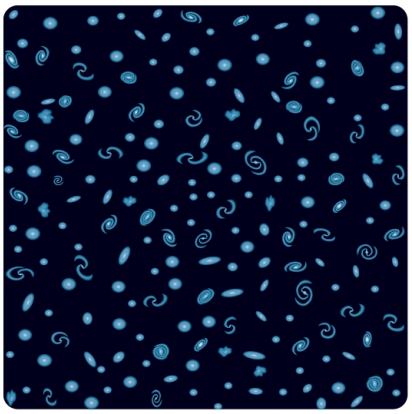
The radiation that comes from great distance has a tremendous redshift. The most distant visible objects are faint galaxies and quasars, with redshifts of about 8; this means their light arrives at Earth with wavelengths nine times longer than when it started the journey. In contrast, the radiation from the hot gas of the big bang is calculated to have a redshift of about 1100. That means the light emitted by the big bang gases arrives at Earth as far-infrared radiation and short-wavelength radio waves. You can't see this radiation with your eyes, but it should be detectable with infrared and radio telescopes. Amazingly, the big bang can still be detected by the radiation it emitted.

In the mid-1960s two Bell Laboratories physicists, Arno Allan Penzias and Robert Woodrow Wilson, were measuring weak radio signals from space (Figure 11.5) when they discovered a peculiar radio noise coming from all directions. At first they attributed this to

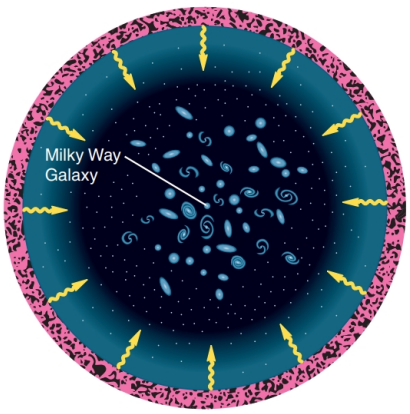
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a A region of the universe during the big bang



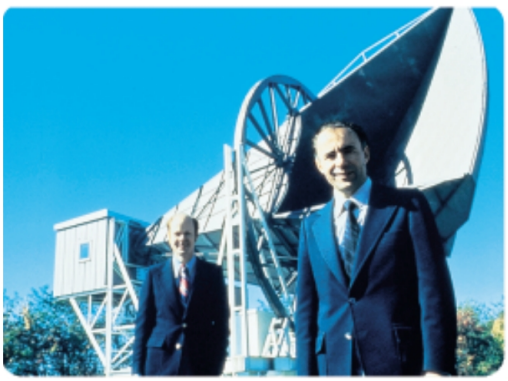
b A region of the universe now



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c The present universe as it appears from our galaxy. In every direction, we see nearby, recently formed galaxies. As we look farther away in every direction, we see light that comes from the early stages of the universe (yellow arrows). The outermost pink ring depicts the earliest stages of the universe. Light from this period just after the big bang reaches us today as infrared and radio energy.

Figure 11.4 This diagram shows schematically the expansion of a small part of the universe. Although the universe is now filled with galaxies, the look-back time distorts what you see. Nearby you can see galaxies, but at greater distances the look-back time reveals the universe at earlier stages. At very great distances, the big bang is detectable as infrared and radio energy arriving from all directions from the hot gas that filled the universe soon after the big bang.



AT&T Archives

Figure 11.5 In 1965, Arno Penzias (right) and Robert Wilson first detected the background radiation left over from the big bang; they used the horn antenna behind them in this photograph.

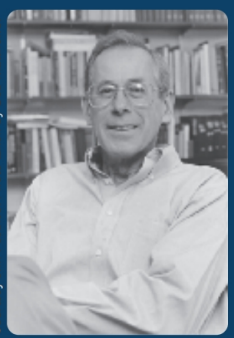
signal errors caused by droppings from pigeons living in the telescope, but the noise persisted even after the birds were removed. Physicists George Gamow and Ralph Alpher had predicted in the 1940s that the big bang would have emitted blackbody radiation that should now be in the far-infrared and radio parts of the spectrum. In the early 1960s, physicist Robert Dicke and his team at Princeton University began building a receiver to detect that radiation. When Penzias and Wilson learned about this earlier work, they realized with the help of Dicke, Peebles, Roll, and Wilkinson that the radio noise—now called the **cosmic microwave background (CMB)**—is actually radiation from the big bang. They received the 1978 Nobel Prize in physics for their discovery. In 1941, the Canadian astronomer Andrew McKellar had measured the temperature of outer space to be about 3K, which corresponded to the energy of the CMB detected by Penzias and Wilson. However, McKellar had passed away in 1960 and did not share in the 1978 Nobel Prize. You can observe the evidence for the big bang yourself on any analog television. When your TV is not tuned to a particular station, the antennas pick up background radio signals, which you can observe as static or snow on your TV screen. About 1 percent of this comes from the CMB radiation left over from the ancient event we now call the big bang.

cosmic microwave background (CMB) Radiation from the hot matter of the universe soon after the big bang. The large redshift makes it appear to come from a blackbody with a temperature of 2.7 K.

The detection of the background radiation was tremendously exciting, but astronomers wanted confirmation. Critical observations in the far-infrared were

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CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Courtesy Jim Peebles. Photo taken by Bob Matthews.

Jim Peebles

Jim Peebles

Phillip James E. Peebles was inspired to study physics as an undergraduate student thanks to four exceptional professors at the University of Manitoba. After graduating in 1958, he moved to Princeton University, where he met his graduate supervisor and mentor Robert Dicke, who sparked his interest in theoretical physics and cosmology. Together, they played a major role in confirming the existence of the cosmic microwave background radiation (CMB), the afterglow of the big bang. The existence and temperature of this background radiation in the universe had been debated since the 1940s. In 1964, when Arno Penzias and Robert Wilson found a source of excess noise in their radio receiver at Bell Laboratories, Peebles and Dicke, together with Peter Roll and David Wilkinson, correctly interpreted this noise to be the CMB. Peebles also correctly calculated the amount of helium in the universe as a result of the big bang. He has made many other important contributions to a variety of topics in cosmology, including the origin of galaxies, large-scale structures in the universe, and the nature of dark matter and dark energy. His book *Physical Cosmology* helped define and guide future studies in cosmology. He is the recipient of numerous awards during his distinguished career, including the 2019 Nobel Prize in physics and the prestigious Eddington Medal. He was also the co-recipient of the first Gruber Cosmology Prize. The Peebles asteroid is named in his honour.

needed to check whether the CMB really has the predicted blackbody spectrum, but they could not be made from the ground. It was not until January 1990 that satellite measurements confirmed that the CMB is blackbody radiation with an apparent temperature of 2.725 +/− 0.002 K, which agrees well with theoretical predictions (Figure 11.6).

It may seem strange that the hot gas of the big bang appears to have a temperature 2.7 degrees above absolute zero, but recall the tremendous redshift. Observers on Earth see light that has a redshift of about 1100; that is, the wavelengths of the photons are about 1100 times longer than when they were emitted. The gas clouds that emitted the photons had a temperature of about 3000 K, and they

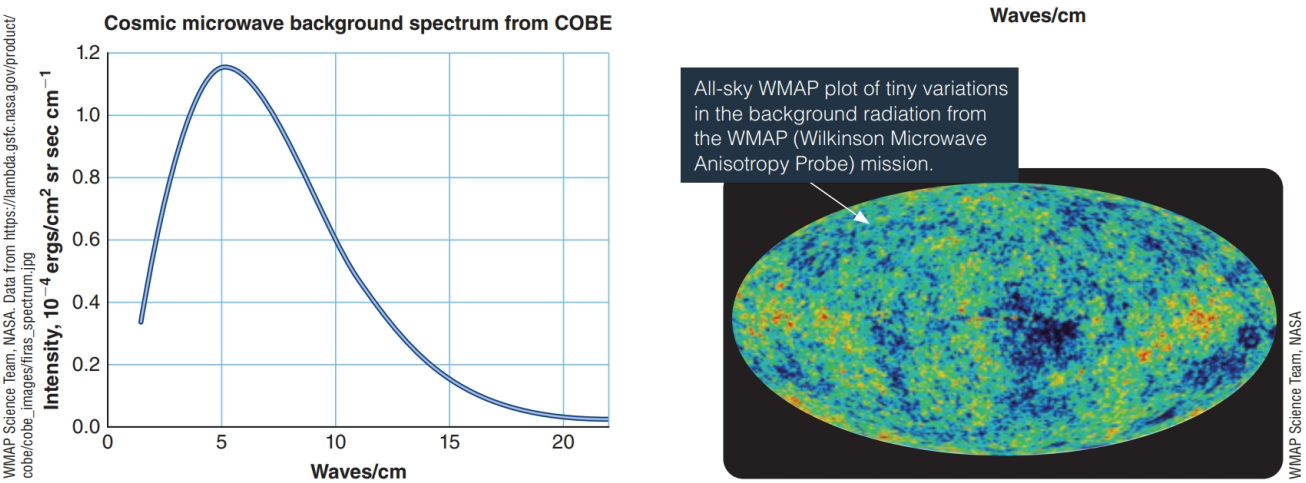


Figure 11.6 When the CMB was first detected in 1965, technology did not allow measurements at many wavelengths. Not until infrared detectors could be put in orbit was it conclusively shown that the background radiation, as predicted by theory, follows a blackbody curve very precisely.

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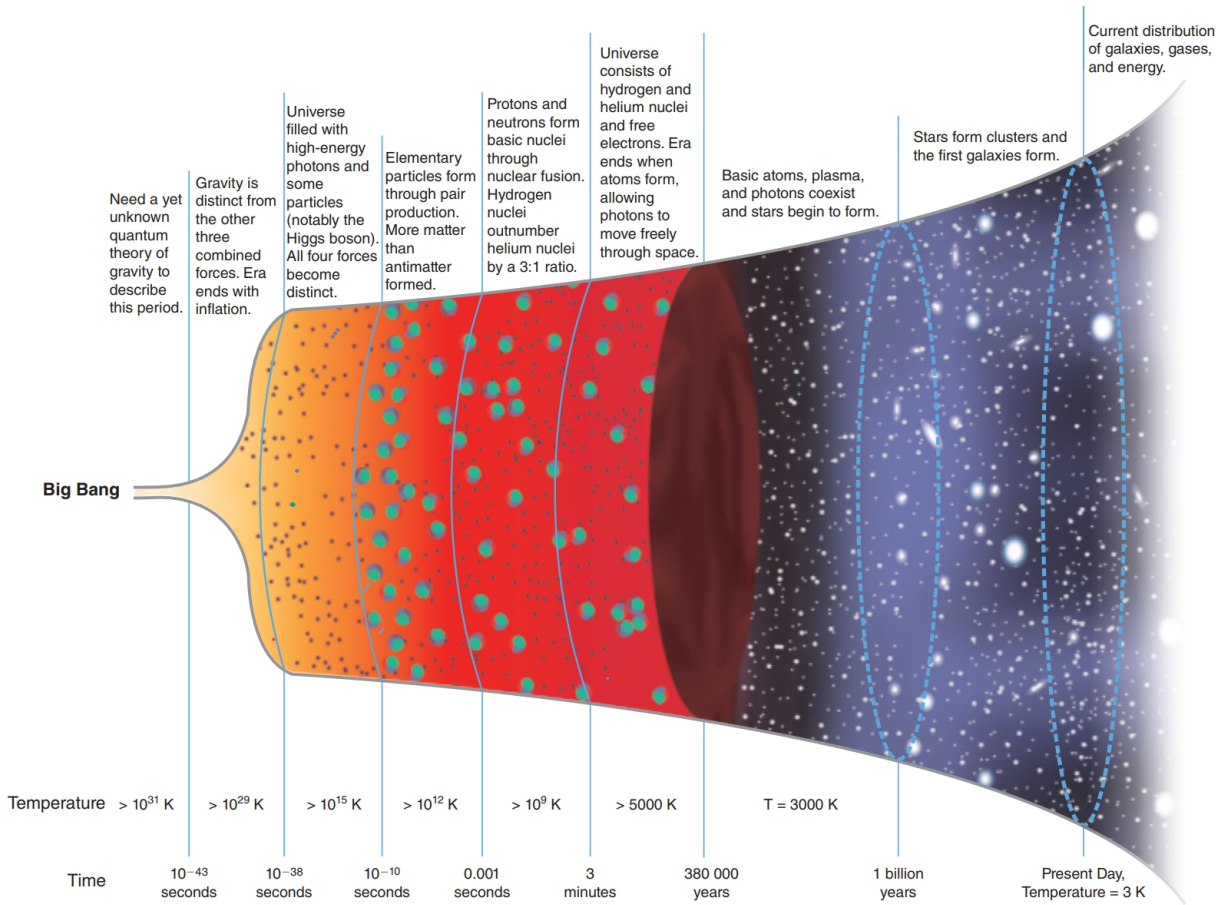


Figure 11.7 A visualization of the history of the universe, showing the important stages in its evolution.

emitted blackbody radiation with a λ_{max} of about 1000 nm. (See further information on Wien's law in Chapter 5 and in **Blackbody Radiation** in the Math Reference Cards.) The expansion of the universe has redshifted the wavelengths about 1100 times longer, so λ_{max} is now about 1 million nm (1 mm). That is why the hot gas of the big bang seems to be 1100 times cooler now, about 2.7 K.

Particles and Nucleosynthesis: The First Seconds and Minutes

Simple observation of the darkness of the night sky and the redshifts of the galaxies tells us that the universe must have had a beginning. Furthermore, the CMB is clear evidence that conditions at the beginning were hot and dense. Theorists combine these observations with knowledge from physics about how atoms and sub-atomic particles behave to work out the story of how the universe evolved after the big bang. You can follow the story of evolution of the universe—particularly the important eras of evolution immediately after the big bang—shown in Figure 11.7.

Cosmologists cannot begin their history of the big bang at time zero, because no one understands the behaviour of matter and energy under such extreme conditions, but they can come amazingly close. One of the largest experimental devices, the Large Hadron Collider (LHC), is capable of generating energies large enough to recreate the conditions at the instant after the big bang (see **Visualizing Astronomy 11.1, The Large Hadron Collider**). If you could visit the universe when it was only one 10-millionth of a second old, you would find it filled with high-energy photons having a blackbody temperature well over 1 trillion (10^{12}) K and a density (using Einstein's equation $E = mc^2$ to calculate the mass equivalent to a certain amount of energy) greater than 5×10^{13} g/cm^3, nearly the density of an atomic nucleus.

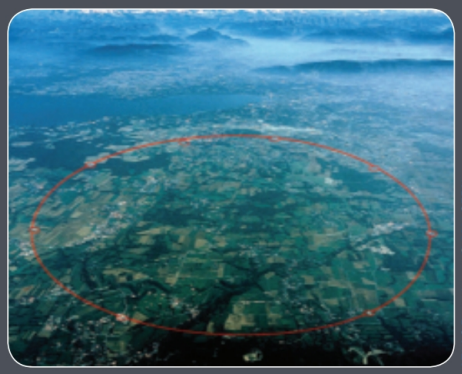
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Visualizing Astronomy 11.1

1 The Large Hadron Collider

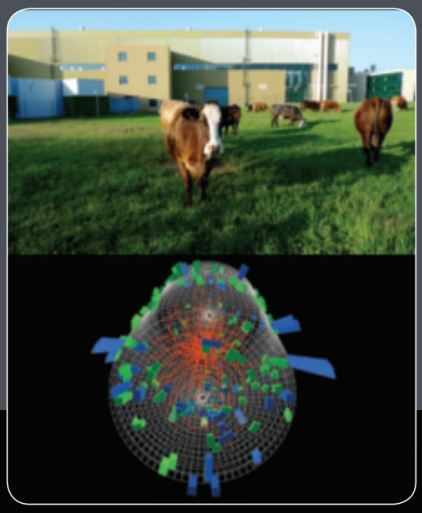
The Large Hadron Collider (LHC) is the largest experiment in history. Designed to explore the most fundamental questions about the universe, the LHC is a particle accelerator and smasher. It produces high-energy collisions of beams of fundamental particles (such as protons), accelerated to 99.9999991 percent of the speed of light, to generate energies large enough to recreate the conditions at the instant after the big bang. To achieve acceleration to such speeds and energies, powerful magnets are used, and cooled to a few degrees above absolute zero (–273°C). The paths of the particle beams also have to be extremely long. This is currently the longest accelerator in the world, with a circular tunnel measuring 27 km in circumference. It is located 100 m under the ground at the border between Switzerland and France. With such high speeds, each proton crosses the French-Swiss border 40 000 times every second!

1a CERN's LHC area, under which the accelerator's tunnel runs, is shown here—near Geneva and Lac Leman, with the French Alps and Mont Blanc in the background.



ATLAS Experiment © 2011 CERN

1b Coexisting worlds: seemingly quiet everyday life, undisturbed by simulations of the big bang and black holes only 100 m below. Concerns were raised by the media and the public regarding experiments generating black holes and the large energies achieved in the accelerator. All of the reports published on the safety of LHC experiments rule out any doomsday scenario. The events created in the LHC experiments occur in nature without any hazard to life. For example, each collision of a pair of protons in the LHC releases an amount of energy comparable to that of a few colliding mosquitoes.

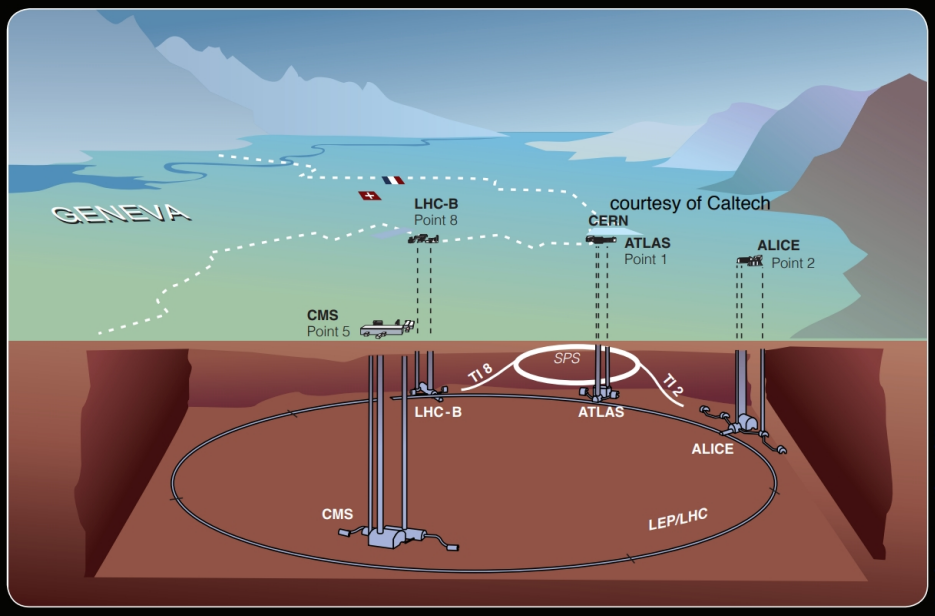


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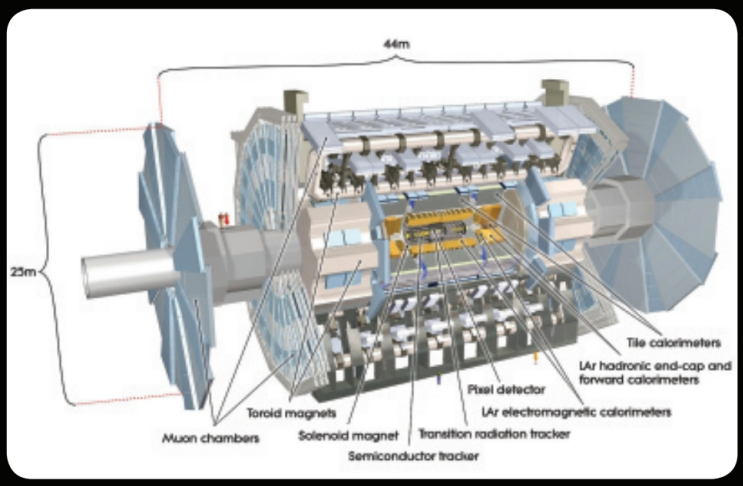
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This diagram shows the locations of the four main experiments (ALICE, ATLAS, CMS, and LHCb) between 50 m and 150 m underground. Three other smaller experiments, called TOTEM, LHCf, and MoEDAL, are also part of the LHC suite of experiments.

All of the collisions are observed in six detectors.



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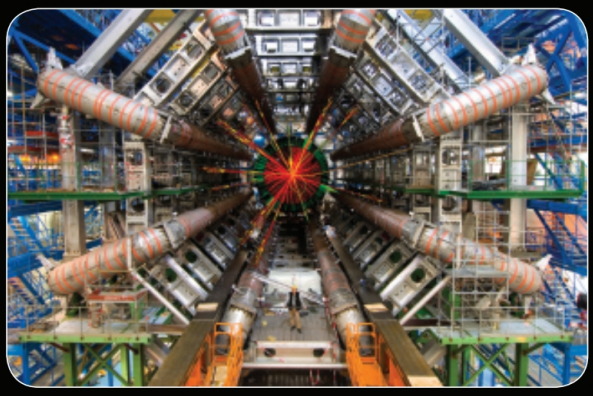
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2a LHC is a large international collaboration, run by CERN—Conseil Européen pour la Recherche Nucléaire (European Organization for Nuclear Research). Around 10 000 scientists around the world are involved in this project. Canada contributed to the LHC by making parts of one of the detectors, ATLAS.

Involving physicists from 38 countries and 174 universities and laboratories the ATLAS detector is one of the largest collaborative efforts ever attempted in the physical sciences. ATLAS is about 45 metres long, has a diameter of 25 metres, is about half as big as the Notre Dame Cathedral in Paris, and weighs about 7000 tons—about the same as the Eiffel Tower, or 1500 elephants.

2b ATLAS detector with graphic simulation of big bang experiment superimposed on the real photograph of the detector. Crashing together in the centre of ATLAS, the particles produce conditions of the early universe and will help shed light on the basic forces that have shaped our universe, the origin of mass, extra dimensions of space, microscopic black holes, and evidence for dark matter candidates in the universe.

In 2012, the discovery of the Higgs boson was announced at CERN after a 40-year search. The discovery of the Higgs particle was the last missing piece of what scientists call the Standard Model, which describes all the fundamental particles and the interactions between them. It explains why particles have mass and is critical for a complete picture of the Standard Model. Further experiments and analysis will be performed over the coming years to verify the discovery and better understand the nature of the Higgs boson.


ATLAS Experiment © 2011 CERN


ATLAS Experiment © 2011 CERN

3 Storing data from numerous experiments poses a large problem in every branch of science today. Data from ATLAS fill up one CD every second (it records only a fraction of the data—those that may show signs of new physics). A worldwide grid of one million computer cores is set up for storage and analysis. It is no surprise or coincidence that the World Wide Web was first created at CERN in 1989.


© 2005 CERN

4 This sculpture of the dancing Shiva at CERN symbolizes the cosmic dance of creation and destruction. Ancient Indian cosmological models were the only ones that discussed time scales for the universe in terms of billions of years. The universe was thought to have been created and destroyed in a recurring cycle that occurred over many billions of years—an ancient precursor to our big bang and big crunch theories today.

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If photons have enough energy, two photons can combine and convert their energy into a pair of particles: a particle of normal matter and a particle of **antimatter**. Particles of antimatter, or "antiparticles," have the same mass as the corresponding particles of regular matter, but have opposite charge. For example, a positron, which is the antiparticle corresponding to the electron, has the same mass as an electron but one unit of positive charge. And when an antimatter particle meets its matching particle of normal matter, the two particles annihilate each other and convert their mass back into energy in the form of two gamma rays. In the early universe, photons had enough energy to produce proton–antiproton pairs or neutron–antineutron pairs. When these particles collided with their antiparticles, they converted their mass back into photons. Thus, the early universe was filled with a dynamic soup of energy flickering from photons into particles and back again.

While all this went on, the expansion of the universe cooled the radiation. By the time the universe was 0.0001 second old, its blackbody temperature had fallen to 10^{12} K. At that point the average energy of the gamma-ray photons fell below the energy equivalent to the mass of a proton or a neutron, so the gamma rays could no longer produce such heavy particles, and the creation of protons and neutrons stopped. Those particles combined with their antiparticles and quickly converted most of the mass into photons.

You might guess from this that all of the protons and neutrons would have been annihilated with their antiparticles, and the universe should now consist of nothing but photons. However, for reasons that are poorly understood, a small excess of normal particles apparently existed. For every billion protons annihilated by antiprotons, one survived with no antiparticle to destroy it. Consequently, you live in a world of normal matter, and antimatter is very rare.

Although the gamma rays did not have enough energy to produce protons and neutrons after the universe fell below 10^{12} K, electron–positron pairs, having lower mass, could still be produced. That continued until the universe was about four seconds old, at which time the expansion had cooled the gamma rays to the point where they could no longer create even electron–positron pairs. Most of the electrons and positrons combined to form photons, and only one in a billion electrons survived. The protons, neutrons, and electrons of which our universe is made were produced during the first four seconds of its history.

antimatter Matter composed of antiparticles, which, upon colliding with a matching particle of normal matter, annihilates, converting the mass of both particles into energy. In comparison to corresponding particles of normal matter, antiparticles have the same mass but opposite charge.

This soup of hot gas and radiation continued to cool. By the time the universe was about two minutes old, protons and neutrons could link to form deuterium, the nucleus of a heavy hydrogen atom, and not be broken apart again. By the end of the next minute, further reactions began converting deuterium into helium, but almost no heavier atoms could be built because there are no stable nuclei with atomic weights of 5 or 8 (in units of the hydrogen atom); these heavier atoms fall apart as soon as they are created. Cosmic element building during the big bang had to proceed rapidly, step by step, like someone hopping up a flight of stairs. The lack of stable nuclei at atomic weights of 5 and 8 meant there were missing steps in the stairway, and the step-by-step reactions had great difficulty jumping over these gaps. Astronomers can calculate that the big bang produced a tiny amount of lithium (atomic weight 7), but no elements heavier than that.

By the time the universe was three minutes old, it had become so cool that most nuclear reactions had stopped, and by the time it was 30 minutes old the nuclear reactions had ended completely. At that time about 25 percent of the mass was in the form of helium nuclei, and the rest was in the form of hydrogen nuclei (protons). That is the abundance of hydrogen and helium observed today in the oldest stars. This evidence provided further confirmation of our model of the big bang. The cosmic abundance of hydrogen and helium was essentially fixed during the first minutes of the universe. The hydrogen nuclei in water molecules in your body have survived unchanged since they formed during the first moments of the big bang. Heavier elements were built by nucleosynthesis inside later generations of stars (see Chapters 8 and 9).

Recombination and Reionization: The First Thousands and Millions of Years

At first the universe was so hot that the gas was totally ionized, and the electrons were not attached to nuclei. Free electrons interact with photons so easily that a photon could not travel very far before it encountered an electron and was deflected (Figure 11.8a). The radiation and matter interacted continuously with each other and cooled together as the universe expanded.

As the young universe expanded, it went through three important changes. First, when the universe reached an age of roughly 50 000 years, the density of the energy present in the form of photons became less than the density of the gas. Before that time, matter could not clump together because the intense sea of photons smoothed the

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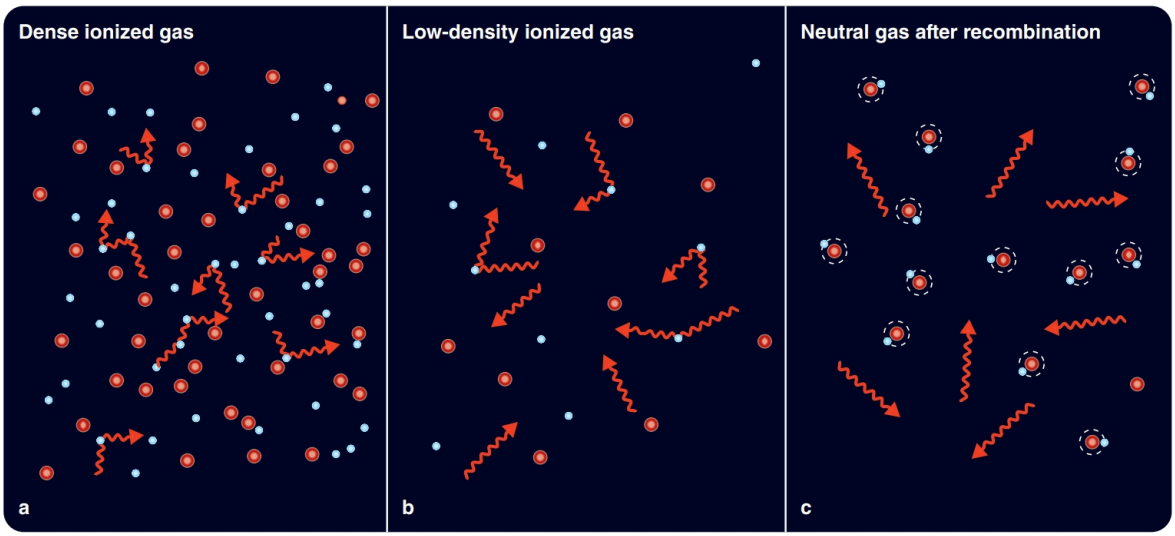


Figure 11.8 Photons easily scatter (bounce) off electrons (blue), but hardly at all from the much more massive protons (red). (a) When the universe was very dense and ionized, photons could not travel very far before they scattered off an electron. This means the gas was opaque. (b) As the universe expanded, the electrons spread farther apart, and the photons could travel farther; this made the gas more transparent. (c) After the era of recombination, most electrons were locked to protons to form neutral atoms, and the universe became almost completely transparent.

gas out. Once the density of the radiation fell below that of matter, the matter could begin to draw together under the influence of gravity and form the clouds that eventually became galaxy clusters and galaxies.

The expansion of the universe spread the particles of the ionized gas farther and farther apart. As the universe reached the age of about 400 000 years, the second important change began. As the density decreased and the falling temperature of the universe reached 3000 K, protons could capture and hold free electrons to form neutral hydrogen. This process is called **recombination**, but *combination* would be more accurate because this was the first time this process occurred. As the free electrons were gobbled up into atoms, they could no longer deflect photons. The photons could travel easily through the gas, so the gas became transparent (Figure 11.8c), and the photons retained the blackbody temperature of 3000 K, which the gas and photons together had at the time of recombination. Those photons are what are observed today as the CMB, with a large redshift that makes their temperature now about 2.7 K.

Recombination left the gas of the big bang neutral, hot, dense, and transparent. At first the universe was filled with the glow of the hot gas, which would have been partly at visible wavelengths. As the universe expanded and cooled, the glow faded, and the universe entered what cosmologists call the **dark age**, a period lasting hundreds of millions of years until the formation of the first stars. During the dark age, the universe expanded in darkness.

The dark age ended as the first stars began to form due to the gravitational attraction of the matter in the universe. The gas from which those first stars formed contained almost no metals and was consequently quite transparent. Mathematical models show that the first stars formed from this metal-poor gas would have been very massive, very luminous, and very short-lived. That first burst of star formation produced enough ultraviolet light to begin ionizing the gas, and today's astronomers, looking back to the most distant visible quasars and galaxies, can see traces of that **reionization** of the universe (Figure 11.9). Reionization marks the end of the dark ages and the beginning of the age of stars and galaxies that continues today.

recombination The stage, within 400 000 years of the big bang, when neutral hydrogen formed and the gas became transparent to radiation.

dark age The period of time after the glow of the big bang faded into the infrared and before the birth of the first stars, during which the universe expanded in darkness.

reionization The stage in the early history of the universe when ultraviolet photons from the first stars ionized the gas that filled space.

Look carefully at Figure 11.9; it summarizes the story of the big bang, from the formation of helium in the first three minutes through energy–matter equality, recombination, and reionization of the gas. It may seem amazing

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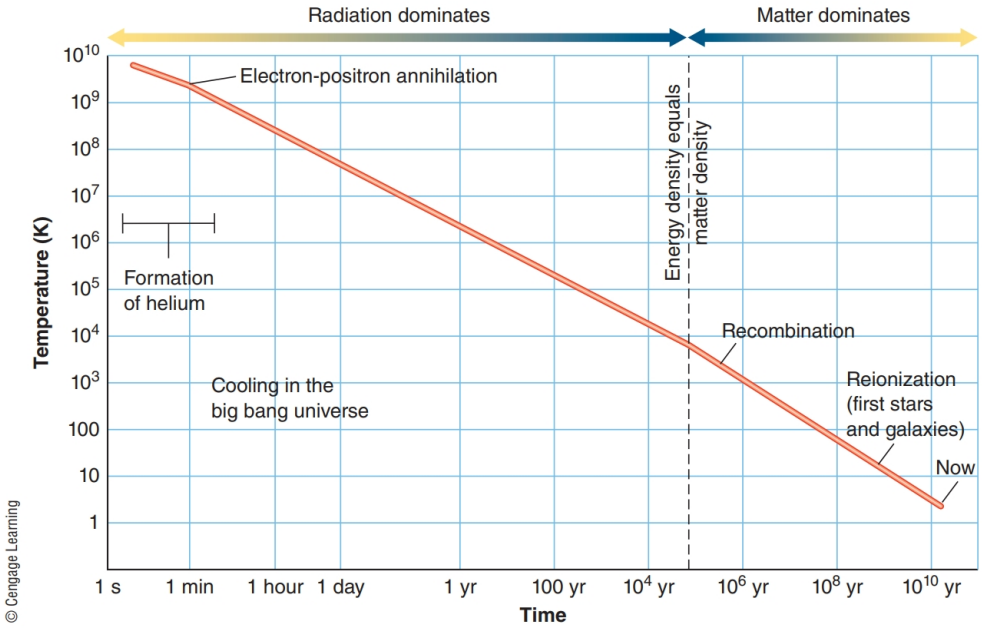


Figure 11.9 During the first few minutes of the big bang, some hydrogen fused to produce helium, but the universe quickly became too cool for such fusion reactions to occur. The rate of cooling increased as matter began to dominate over radiation. Recombination freed the radiation from the influence of the gas, and the birth of the first stars caused reionization. Note how the exponential scale in time stretches early history and compresses recent history.

that mere humans trapped on Earth can draw such a diagram, but remember that it is based on evidence and on the best understanding of how matter and energy interact.

11.3 Space and Time, Matter and Energy

How can the big bang have happened everywhere? To solve the puzzle, you must put what seem to be reasonable expectations on hold and look carefully at how space and time behave on cosmic scales.

isotropy The observation that, in its general properties, the universe looks the same in every direction.

homogeneity The observation that, on the large scale, matter is uniformly spread through the universe.

cosmological principle The assumption that any observer in any galaxy sees the same general features of the universe.

Looking at the Universe

The universe looks about the same whichever way you look. That is called **isotropy**. Of course, there are local differences. If you look toward a galaxy cluster you see more galaxies, but that is only a local variation. On the average, you see similar numbers of galaxies in every direction. Furthermore, the background radiation is also almost perfectly uniform across the sky. The universe is observed to be highly isotropic, almost exactly the same in all directions when viewed from our position.

The universe also seems to be homogenous; **homogeneity** is the property of being the same everywhere. Of course there are local variations. Some regions contain more galaxies and some fewer. Also, as the universe evolves, at large look-back times you see galaxies at an earlier stage. When we account for these well-understood variations, the universe seems to be, on average, the same everywhere. This is harder to check because we can't actually go to the locations of distant galaxies and check in detail that things are about the same there as here, but all astronomical observations indicate this is so.

Isotropy and homogeneity together lead to the **cosmological principle**. According to the cosmological principle, any observer in any galaxy sees that the universe has the same general properties, after accounting for relatively minor local and evolutionary variations. This principle implies that there are no special places in the universe. What you see from the Milky Way Galaxy is typical of what all intelligent creatures see from their respective home galaxies. Furthermore, the cosmological principle is another

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way of saying that the universe has no centre or edge. Such locations would be special places, and the cosmological principle means there are no special places.

The Cosmic Redshift

Distance is the separation between two points in space; time is the separation between two moments. Einstein's theories of special relativity and general relativity (published, respectively, in 1905 and 1916) describe how space and time are related and can be considered together as the fabric of the universe: space-time. You can think of space-time as the canvas on which the universe is painted. Einstein's theories predict that the canvas of space-time can potentially expand (or contract); amazingly, this has been confirmed by observations.

The stretching of space-time explains one of the most important observations in cosmology: cosmological redshifts. Modern astronomers understand that, except for small local motions within clusters of galaxies, the galaxies are basically at rest and have kept approximately the same "address" in space since they formed after the big bang. The distances between them increase as space-time expands. Furthermore, as space-time expands, it stretches photons travelling through space to longer wavelengths (see Figure 11.10). Photons from distant galaxies spend more time travelling through space and are stretched more than photons from nearby galaxies. That is why redshift depends on distance.

Astronomers often express redshifts as if they were radial velocities, but the redshifts of the galaxies are not Doppler shifts. That is why this book is careful to refer to a galaxy's *apparent* velocity of recession. All a cosmological redshift tells you directly is how much the universe has expanded since the light began its journey to Earth. The formula to calculate the distance a photon has travelled, given its redshift, is complicated, and not all the parameters have been measured precisely. Nevertheless, Hubble's law does apply, and redshifts can be used to estimate the distances to galaxies.

open universe A model of the universe in which space-time is curved in such a way that the universe is infinite.

closed universe A model of the universe in which space-time is curved to meet itself, and the universe is finite.

flat universe A model of the universe in which space-time is not curved.

Model Universes

Almost immediately after Einstein published his theory, theorists were able to solve the highly sophisticated mathematics to compute simplified descriptions of the behaviour of space-time and matter. Those "model universes" dominated cosmology throughout the 20th century.

The equations allowed three general possibilities. Space-time might be curved in ways that are called an **open universe** or a **closed universe**, or space-time might have no overall curvature at all, a situation that is called a **flat universe**. Most people find the curved space-time models difficult to imagine. Fortunately, modern observations have shown that the flat universe model is almost certainly correct. Note that *flat* does not mean two dimensional. Rather, it means that the familiar rules of geometry you learned in elementary and high school—for instance, that the circumference of a circle is 2π times its radius and that the interior angles of a triangle add up to 180 degrees—are true on the largest scales. Different rules of geometry would apply on large scales if the universe were curved.

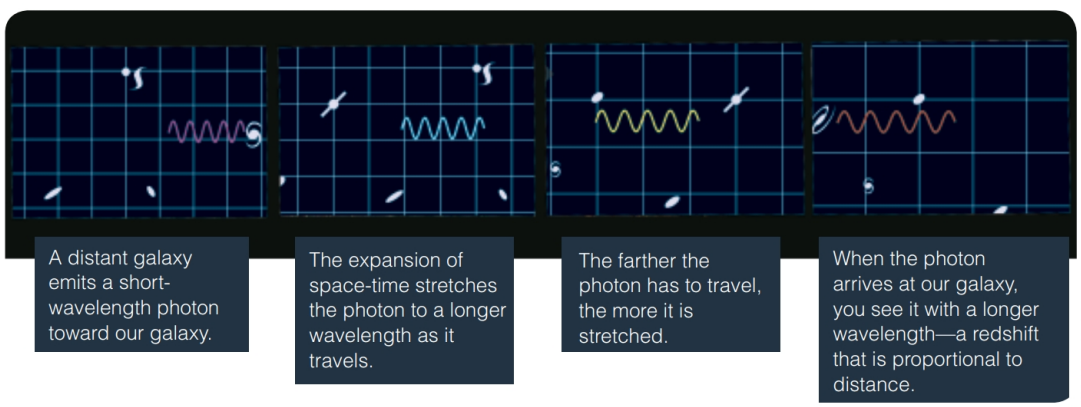


Figure 11.10 As the universe (space-time) expands, the light waves become stretched to longer wavelengths.

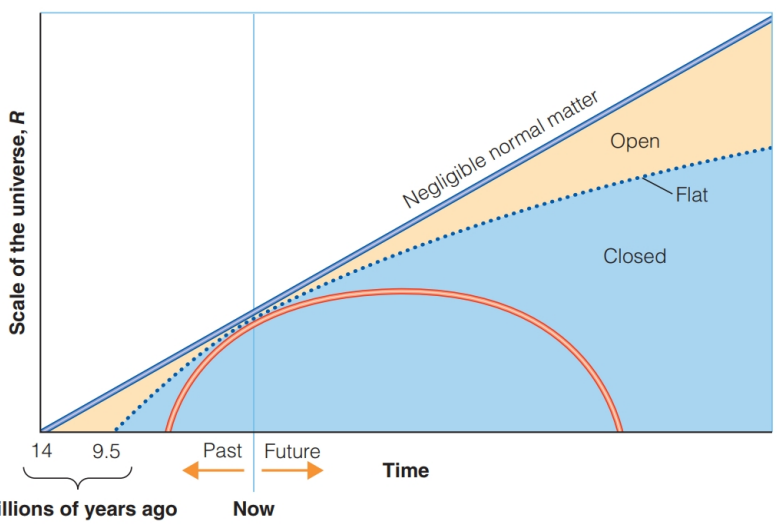
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critical density The average density of matter and energy in the universe needed to make its curvature flat.

nonbaryonic matter Proposed dark matter made up of particles other than protons and neutrons (baryons).

A main criterion separating the three models is the average density of the universe, which, according to general relativity, determines the overall curvature of space-time. If the average density of matter and energy in the universe equals what is called the **critical density**, calculated to be about 1×10^{-29} g/cm^3 (depending on the exact value of the Hubble constant), space-time is flat. If the average density is more than the critical density, this would cause greater space-time curvature and the universe must be closed; if it is less, the universe must be open.

The expansions versus time of the three different models are compared in Figure 11.11. The parameter *R* on the vertical axis is a measure of the extent to which the universe has expanded. You could think of it, essentially, as the average distance between galaxies. In this figure you can see that closed universes may expand and then contract, and open universes may expand forever. Notice also that each of the three curves intersects the horizontal axis at a different point. The distance between the present and this intersection point gives the age of the universe. Therefore, you need to know whether the universe is open, flat, or closed to estimate the age of the universe. The Hubble time, discussed earlier in this chapter as a rough estimate of the age of the universe, is actually the age the universe would be if it were totally open; this means it would have to contain almost no matter at all.



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Figure 11.11 Illustrations of some simple universe models that depend only on the effect of gravity. Under that assumption, open universe models expand without end, and the corresponding curves fall in the region shaded orange. Closed models expand and then contract again (the red curve is one example). A flat universe (dotted line) marks the boundary between open and closed universe models. The relationship between the estimated age and actual age of the universe depends on the geometry of space-time. The age of the universe for each model is shown on the graph as the horizontal distance from "Now" back to the time when the universe scale factor *R* equalled 0.

Dark Matter in Cosmology

Later in this chapter you will see how observational evidence indicates that the universe is probably flat. But this leads to a different problem. If the universe is flat its average density must equal the critical density, yet when astronomers added up the matter they could detect they found only a few percent of the critical density. They wondered if the dark matter made up the rest.

In Chapters 9 and 10, you learned that our galaxy, other galaxies, and galaxy clusters have much stronger gravitational fields than expected based on the amount of visible matter. Even when you add in the nonluminous gas and dust that you expect to find, their gravitational fields are stronger than expected. Galaxies must contain dark matter—in fact, much more dark matter than normal matter (refer to Figures 9.8 and 9.9).

The protons and neutrons that make up normal matter, including Earth and you, belong to a family of subatomic particles called *baryons*. Modern evidence based on what can be determined about the products of nuclear reactions in the first few minutes after the big bang shows that the dark matter is not baryonic. If there were lots of baryons present during those early moments, they would have (1) collided with and destroyed deuterium nuclei, and (2) collided with some of the helium to make lithium.

Figure 11.12 shows that the observed amount of deuterium sets a lower limit on the density of the universe, and the observed abundance of lithium-7 sets an upper limit. Those limits indicate that the baryons you and Earth and the stars are made of cannot add up to more than 4 percent of the critical density. Yet observations show that galaxies and galaxy clusters contain as much as 30 percent of the critical density in the form of dark matter. Only a small amount of the matter in the universe can be baryonic, so the dark matter must be **nonbaryonic matter**.

The true nature of dark matter remains one of the mysteries of astronomy. The

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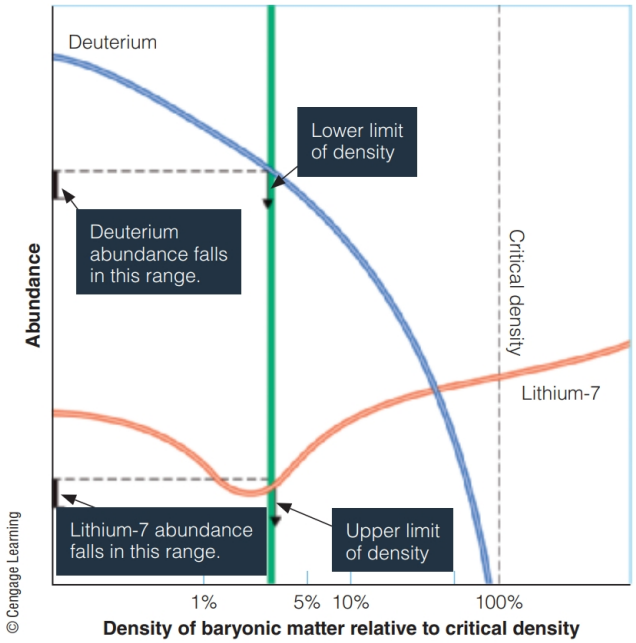


Figure 11.12 This diagram compares observation with theory. Theory predicts how much deuterium and lithium-7 you would observe for different densities of normal matter (red and blue curves). The observed density of deuterium falls in a narrow range shown at upper left and sets a lower limit on the possible density of normal matter. The observed density of lithium-7 sets an upper limit. This means the true density of normal matter must fall in a narrow range represented by the green column. Certainly, the density of normal matter is much less than the critical density.

most successful models of galaxy formation require that the dark matter be made up of **cold dark matter**, meaning the particles move slowly and can clump into structures with sizes that explain the galaxies and galaxy clusters you see today. There are several experiments around the world focusing on trying to detect dark matter. These include underground labs in Boulby, UK; Minnesota, USA; and Sudbury, Canada (SNOLAB).

Although the evidence is very strong that dark matter exists, it is not abundant enough by itself to make the universe flat. Dark matter appears to constitute no more than about 30 percent of the critical density. As you will see later in this chapter, there is more to the universe than meets the eye and more even than dark matter.

11.4 Modern Cosmology

If you are a little dizzy from the weirdness of expanding space-time and dark matter, make sure you are sitting down before you read further. As the 21st century began, astronomers made a discovery that startled all cosmologists: the expansion of the universe is actually accelerating. To get a running start on these new discoveries, you'll have to go back a couple of decades.

Inflation

By 1980, the big bang model was widely accepted, but it faced two problems that led to the development of an improved theory—a big bang model with an important addition.

One of the problems is called the **flatness problem**. The curvature of space-time seems to be near the transition between an open and a closed universe. That is, the universe seems approximately flat. It seems peculiar that the actual density of the universe is anywhere near the critical density that would make it flat. To be so near critical density now, the density of the universe during its first moments must have been very close, within 1 part in 10^{49} of the critical density. So the flatness problem is, *Why was the universe so close to exactly flat, with no space-time curvature, at the time of the big bang?*

The second problem with the original big bang theory is called the **horizon problem**. When astronomers correct for the motion of Earth, they find that the CMB is very isotropic, the same in all directions to a precision of better than 1 part in 1000. However, background radiation coming from two points in the sky separated by more than an angle of one degree is from two parts of the big bang that were far enough apart that they should not have been connected at any previous time. That is, when the CMB photons were released, the universe was not old enough for energy to have travelled at the speed of light from one of those regions to the other—the regions should always have been beyond each other's "horizon" and could not have exchanged heat to make their temperatures equal. So the horizon problem is, *How did every part of the observable universe get to be so nearly the same temperature by the time of recombination?*

The key to these two problems and to other problems with the simple big bang model may lie with a modified model called the

cold dark matter Dark matter that is made of slow-moving particles.

flatness problem The peculiar circumstance that the early universe must have contained almost exactly the right amount of matter to make space-time flat.

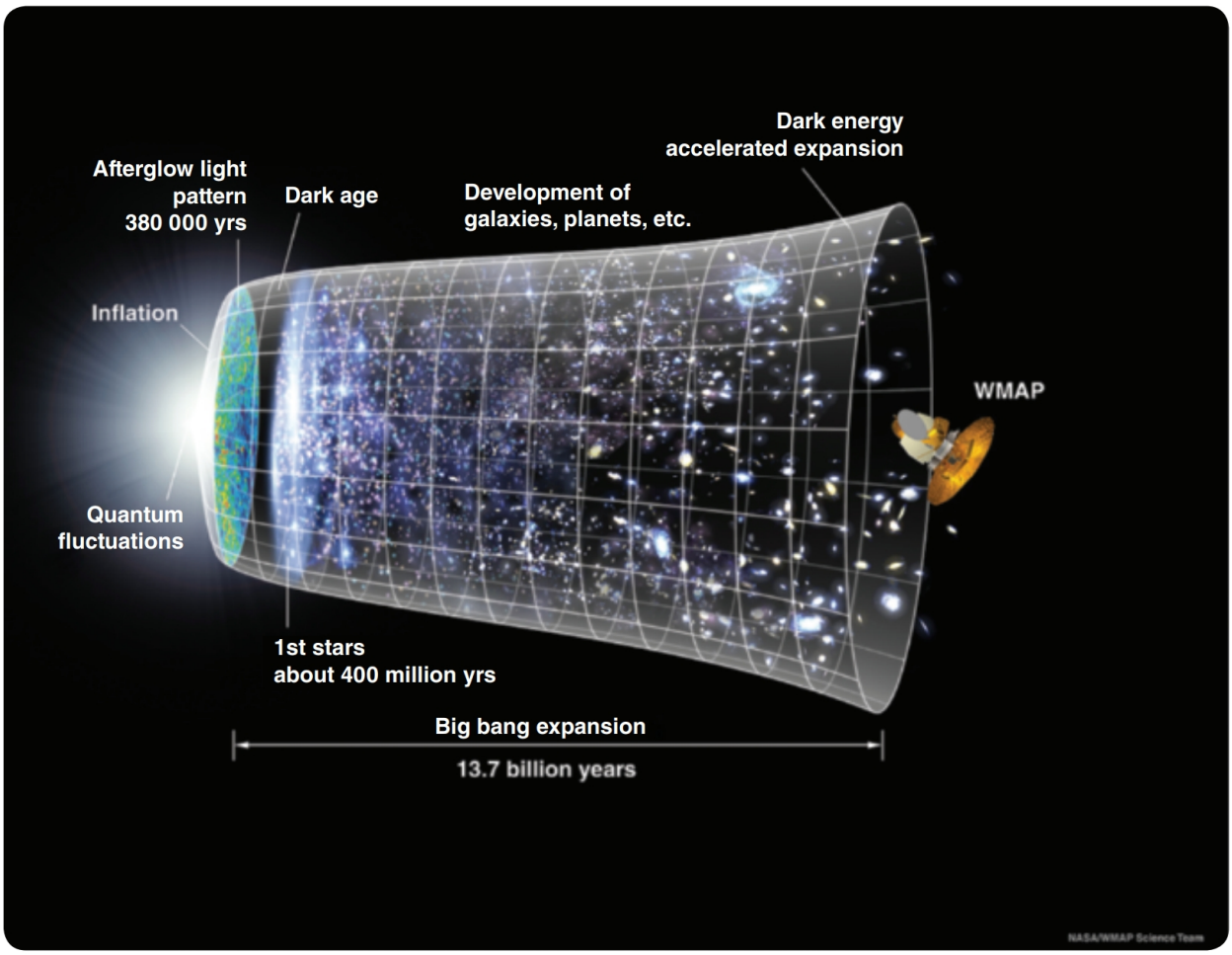
horizon problem The circumstance that the primordial background radiation seems much more isotropic than can be explained by the standard big bang theory.

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inflationary big bang A version of the big bang theory, derived from grand unified theories of particle physics, that includes a rapid expansion when the universe was very young.

inflationary big bang that predicts there was a sudden extra expansion when the universe was very young, even more extreme than that predicted by the original big bang model. According to the inflationary universe model, the universe expanded and cooled until about 10^{-36} seconds after the big bang. Then the universe became cool enough that the forces of nature (see Chapter 7), which at earlier extremely high temperatures would have behaved identically, began to differ from each other. Physicists calculate this would have released tremendous amounts of energy and suddenly inflated the universe by a factor of 10^{50} or larger. Inflation ended 10^{-32} seconds after the big bang. As a result, the part of the universe that is now visible from Earth, the entire observable universe, expanded rapidly from 35 orders of magnitude smaller than a proton to roughly a metre across, and then continued a slower expansion to its present state. Figure 11.13 illustrates the history of the universe and its expansion process—inflation, followed by slowing of the expansion rate, followed by an increased rate of expansion.

Sudden inflation can solve both the flatness problem and the horizon problem. The inflation of the universe would have forced whatever curvature it had toward zero, just as inflating a balloon makes a small spot on its surface flatter. You now live in a universe that has almost perfectly flat space-time geometry because of that sudden inflation long ago. In addition, because the observable part of the universe was no larger in volume than an atom



NASA/WMAP Science Team

Figure 11.13 A schematic of the expansion of the universe from the big bang to present day. Less than a moment after the big bang, a period of rapid expansion—known as inflation—occurred, followed by a long period of slowing expansion over billions of years, due to the gravitational pull of the matter in the universe. Recent measurements indicate that a repulsive force termed dark energy overcame the pull of gravity about 6 billion years ago and resulted in an increasing expansion rate. (The current estimate for the age of the universe is 13.8 billion years.)

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before inflation, it was small enough to have equalized its temperature by then. Now you live in a universe that has the same CMB temperature in all directions.

The inflationary theory predicts that the universe is almost perfectly flat. Observations, however, give evidence that the masses scientists know about (baryonic matter plus dark matter) add up only to about 30 percent of the amount needed to make space-time flat. Can there be more to the universe than baryonic matter and dark matter? What could be weirder than dark matter? Read on.

The Acceleration of the Universe

Both common sense and mathematical models suggest that as the galaxies recede from each other the expansion should be slowed by gravity trying to pull the galaxies toward each other. How much the expansion is slowed should depend on the amount of matter in the universe. If the density of matter is less than the critical density, the expansion should be slowed only slightly, and the universe should expand forever. If the density of matter in the universe is greater than the critical density, the expansion should be slowing down dramatically, and the universe should eventually begin contracting.

For decades, astronomers struggled to measure the distance to very distant galaxies directly, compare distances with redshifts, and thereby detect the slowing of the expansion. The rate of slowing would in turn reveal the true curvature of the universe. This was one of the key projects for the Hubble Space Telescope. Two international teams of scientists used the Hubble telescope as well as telescopes in Hawaii, Chile, and Australia to study the expansion of the universe. They calibrated type Ia supernovae as standard candles by locating such supernovae that occur in nearby galaxies whose distances were known from Cepheid variables and other reliable distance indicators (see Chapter 10). Once they determined the peak luminosity of type Ia supernovae, they could use that information to find the distances of much more distant galaxies. They also observed the redshifts of these galaxies and calculated how fast they were moving away, thus estimating the rate of expansion of the universe.

Both teams announced their results in 1998. They agreed that the expansion of the universe is not slowing down. Contrary to expectations, it is speeding up! In other words, the expansion of the universe is accelerating (Figure 11.14). In 2011, the leaders of the two teams—Saul Perlmutter, Brian Schmidt, and Adam Riess—were awarded the Nobel Prize in physics for this amazing discovery.

The announcement that the expansion of the universe is accelerating was totally unexpected, and astronomers immediately began testing it. The most likely problem was thought to be that the calibration of the supernovae by the original teams might be incorrect. However, that type of problem has been ruled out by measurements of more recently discovered supernovae at very great distances. Other possible problems have been checked and appear to have been eliminated. The universe really does seem to be expanding faster and faster.

Dark Energy and Acceleration

If the expansion of the universe is accelerating, there must be a force of repulsion in the universe, and astronomers are struggling to understand what it could be. One possibility leads back to Albert Einstein.

When Einstein published his theory of general relativity in 1916, he noticed that his equations describing space-time implied that the universe should contract because of the gravitational attraction of galaxies for each other. Einstein thought he needed to balance the attractive force of gravity by adding a constant to his equations called the **cosmological constant**, representing a force of repulsion. The balancing of the attractive and repulsive forces would then describe a universe in equilibrium. However, 13 years later, in 1929, Edwin Hubble announced that the universe was not in equilibrium, but was expanding. Einstein assumed that this expansion explained why gravity was not causing the universe to collapse on itself and said that introducing the cosmological constant was his biggest blunder. Given the discovery of dark energy, modern astronomers aren't so sure.

One explanation for the acceleration of the universe is that there is a cosmological constant after all, representing a real force that drives a continuing acceleration in the expansion of the universe. The cosmological constant, as its name implies, would be constant in strength over time. Another possibility is a type of energy that is not constant in strength over time. Astronomers have begun referring to this type of energy as **quintessence**. In either case, the observed acceleration is evidence that some form of energy, either a cosmological constant or quintessence, is spread throughout space. Astronomers refer to this as **dark energy**, energy

cosmological constant A constant in Einstein's equations of space and time that represents a force of repulsion.

quintessence A possible form of dark energy that can change in strength as the universe ages.

dark energy The energy believed to drive the acceleration of the expanding universe.

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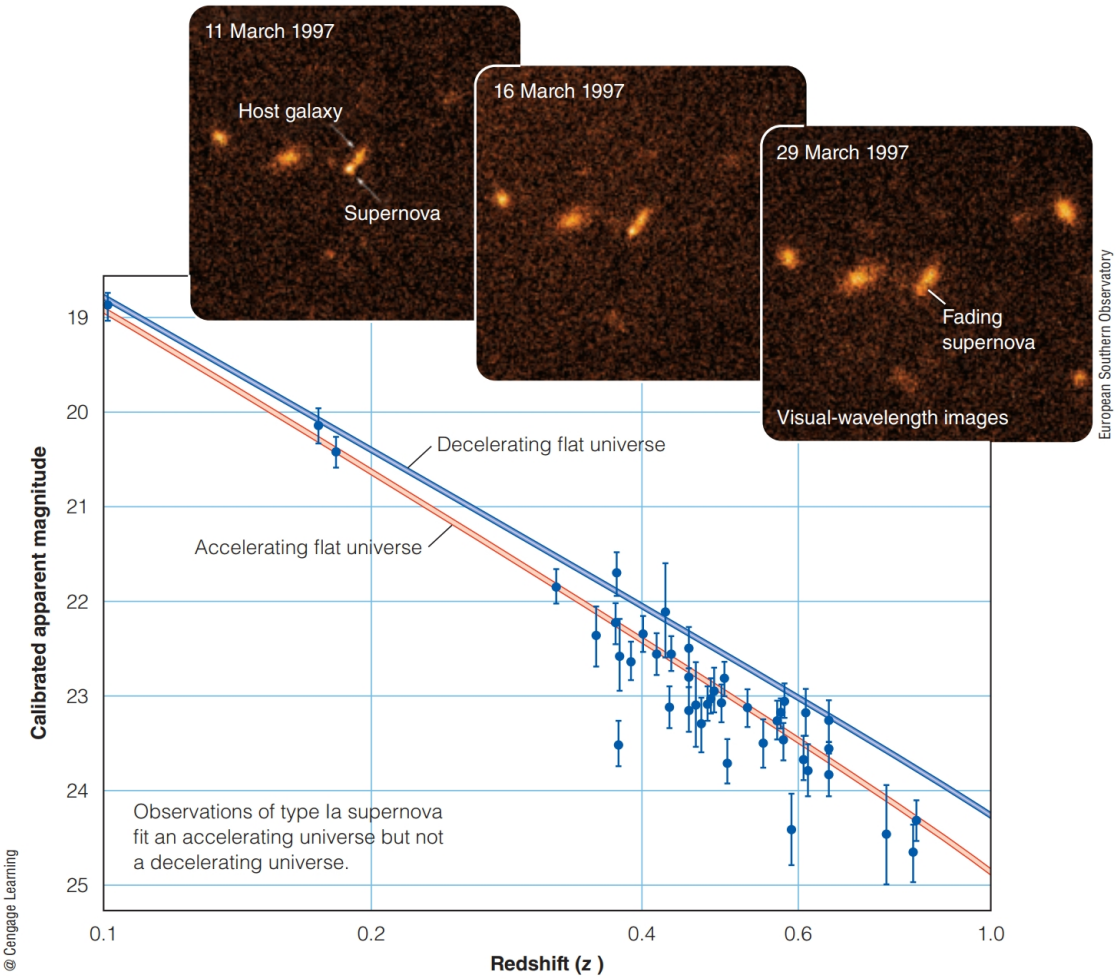


Figure 11.14 From the way supernovae fade over time, astronomers can identify those that are type Ia. Once calibrated, those supernovae can be compared with their redshifts, revealing that distant type Ia supernovae are about 25 percent fainter than expected. That must mean they are farther away than expected, given their redshifts. This is strong evidence that the expansion of the universe is accelerating.

that drives the acceleration of the universe but does not contribute to starlight or the CMB. Understanding the nature of dark energy is one of the most important and interesting scientific challenges today.

Acceleration and dark energy were first discovered when astronomers found that supernovae a few billion light-years away were slightly *fainter* than expected. Since then even more distant supernovae have been determined to be a bit *brighter* than expected, meaning they are not as far away as the redshifts of their galaxies would seemingly indicate. This means that sometime about 6 billion years ago the universe shifted gears from deceleration to acceleration. The careful calibration of type Ia supernovae allows astronomers to observe this change from deceleration to acceleration. This discovery has the important consequence of increasing previous estimates of the age of the universe by several billion years.

Dark energy can also help you understand the lack of curvature of space-time. The theory of inflation makes the specific prediction that the universe is flat. Dark energy seems to fit with that prediction. As mentioned earlier in this chapter, energy and matter are equivalent, so dark energy is equivalent to mass spread through space. Baryonic matter plus dark matter makes up about a third of the critical density, and dark energy appears to make up two-thirds. That is, when you include dark energy, the total mass-plus-energy density of the universe equals the critical density, making the universe flat.

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The Fate of the Universe

For many years, cosmologists enjoyed saying: "Geometry is destiny." Thinking about models of open, closed, and flat universes, they concluded that the density of a model universe determines its geometry, and its geometry determines its fate. In other words, they were sure that an open universe must expand forever, and a closed universe must eventually begin contracting. That is true, however, only if the universe is ruled by gravity. If the power of dark energy dominates gravity, then geometry is not destiny, and even a closed universe might expand forever.

The ultimate fate of the universe depends on the nature of dark energy. If dark energy is described by the cosmological constant, the force driving acceleration does not change with time, and our flat universe will expand forever. The galaxies will get farther and farther apart, use up their gas and dust making stars, and the stars will ultimately all die, until each galaxy is isolated, burnt out, dark, and alone. If, however, dark energy is described by quintessence, its strength could increase with time, and the universe expansion may accelerate faster and faster as space pulls the galaxies away from each other and eventually pulls the galaxies apart, then pulls the stars apart, and finally rips individual atoms apart. This has been called the **big rip**. Don't worry. Even if a big rip is in the future, nothing will be happening for at least 30 billion years.

There will probably be no big rip. Researchers in France and Canada used images of distant supernovae from the Canada-France-Hawaii Telescope in Hawaii to show that dark energy is described by Einstein's cosmological constant to within 10 percent. Furthermore, important observations made by the Chandra X-ray Observatory have been used to measure the amount of hot gas and dark matter in 25 galaxy clusters. These observations are important for two reasons. First, the redshifts and distance of these galaxies confirm that the universe expansion initially slowed down, but then shifted gears about 6 billion years ago and is now accelerating. The results are also important because they are almost good enough to rule out quintessence. If dark energy is described by the cosmological constant and not by quintessence, then there will be no big rip (Figure 11.15). Notice that this method does not depend on type Ia supernovae at all, so it provides an independent confirmation that acceleration is real. When a theory is confirmed by observations of many different types, scientists have much more confidence that it is a true description of nature.

big rip The fate of the universe if dark energy increases with time, and galaxies, stars, and even atoms are eventually ripped apart by the accelerating expansion of the universe.

A New Way to Observe the Universe

In order to better understand the nature of dark energy scientists need to confirm whether it is indeed described

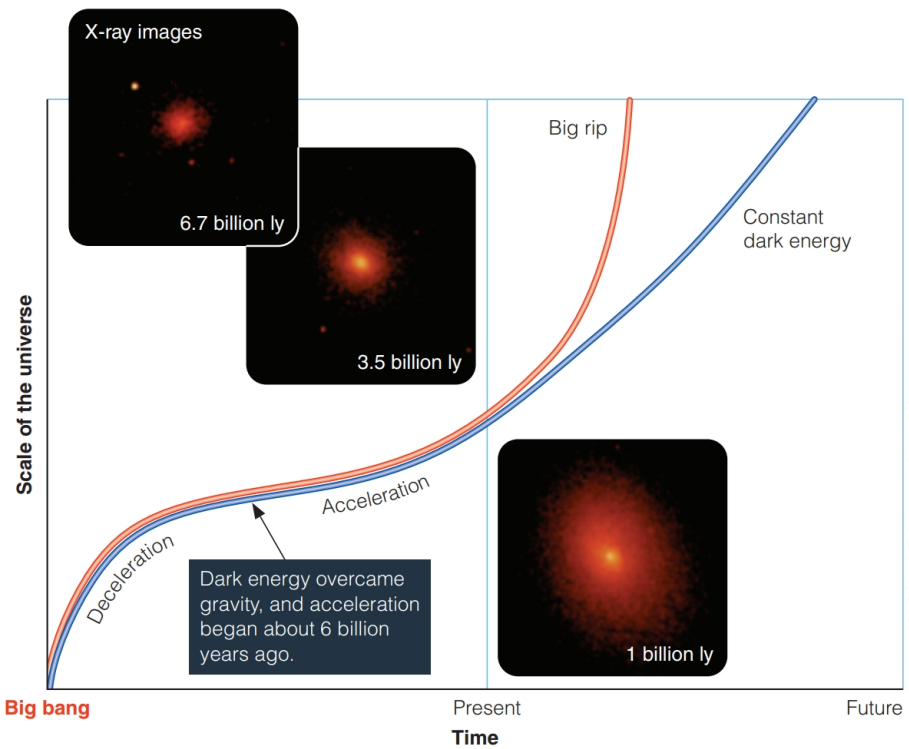
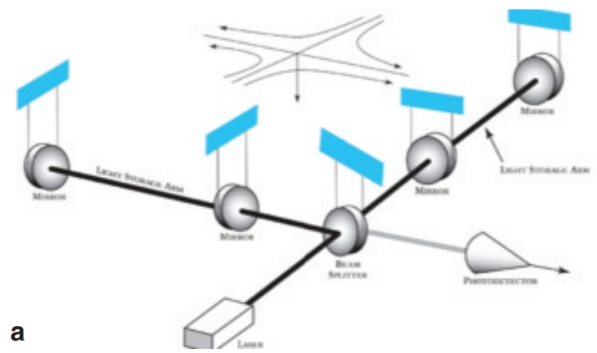


Figure 11.15 X-ray observations of hot gas in galaxy clusters confirm that in its early history the universe was decelerating because gravity was stronger than the dark energy. As expansion weakened the influence of gravity, dark energy began to produce acceleration. The evidence is not conclusive, but it most directly supports the cosmological constant and weighs against quintessence, which means the universe may not face a big rip. This diagram is only schematic, and the two curves are drawn separated for clarity; at the present time the two curves have not diverged from each other.

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by the cosmological constant in Einstein's equations of general relativity. So it's important to keep probing and testing Einstein's theory at all scales. One way to do so is to study the interactions between massive objects. As you learned in Chapter 8.7, the motion of massive objects such as binary stars can cause ripples in space-time known as gravitational waves. These gravitational waves can travel billions of light-years and reach Earth, so they give us an opportunity to study strong gravitational interactions of very distant massive objects. However, our telescopes on Earth are designed to detect electromagnetic radiation and cannot detect gravitational waves. A new type of detector is required to observe these space-time oscillations. The first attempts to build such a detector began in the 1960s, and by the 1970s scientists believed that a detector sensitive enough to detect gravitational waves could be built. It would take decades and the work of hundreds of scientists to turn the idea into reality. The result was LIGO—the Laser Interferometer Gravitational-Wave Observatory—one of the largest and most ambitious experiments ever built.

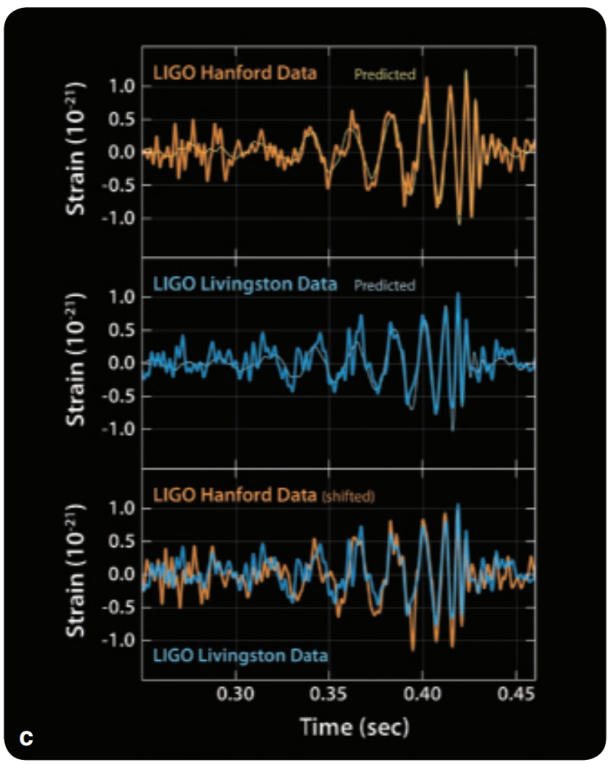
LIGO is designed to detect tiny changes in the path travelled by a laser beam. Two laser beams are initially set up to travel along two perpendicular paths of identical length (Figure 11.16). A gravitational wave is a ripple in space-time so it would cause space itself to oscillate—getting stretched along one direction and squeezed along the perpendicular direction and vice versa. Thus when a gravitational wave passes, the two paths that the laser beams travel get alternately stretched and squeezed by the ripples so that the two path lengths are no longer identical. This oscillation in the path lengths can be detected as an interference pattern between the two beams of light. The accuracy of the detector increases with the path lengths travelled by the laser beams. The two perpendicular arms of the LIGO interferometer along which the laser beams travel are 4 km long. The laser beams make 280 round trips in each arm to dramatically increase the sensitivity so that a tiny change in path length 10 000 times smaller than the width of a proton can be detected. The interferometer is operated in a vacuum and carefully isolated from any external



(a) Caltech/MIT/LIGO Lab



(b) Caltech/MIT/LIGO Lab



(c) LIGO

Figure 11.16 (a) Setup of the LIGO interferometer showing the perpendicular paths of identical length travelled by laser beams. When a gravitational wave (shown above) passes through the interferometer, the two arms get squeezed and lengthened alternately, changing the lengths of the arms and creating an interference pattern in the laser light that can be detected. (b) Photo of the 4-km arms of the LIGO detector in Hanford, the United States. (c) The first observed gravitational wave signal measured by the two LIGO detectors, corresponding to the collision of two distant black holes.

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noise that could cause a false signal. Despite all this, a single interferometer is still not enough to unmistakably identify a gravitational wave signal and rule out all other sources of vibrations. So two such interferometers were built in the USA; one in Livingston, and the other in Hanford, 3002 km away. It can be confirmed using the other interferometer.

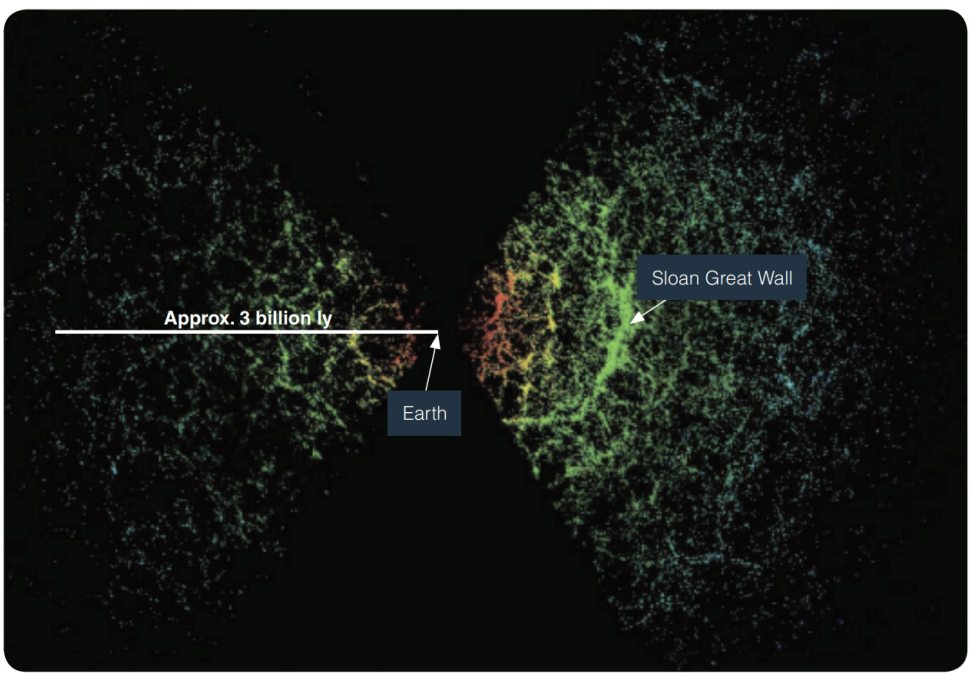
In September 2015, LIGO first detected a gravitational wave. The observed interference pattern of light, detected at both LIGO locations, matched the predictions of general relativity for the collision of two black holes (Figure 11.16). This historic observation marked the beginning of the field of gravitational-wave astronomy—a whole new way to observe the universe. In particular, gravitational waves can provide scientists with data from very strong gravitational interactions to test the accuracy of Einstein's theory of general relativity, something that had not been possible before LIGO. As more detectors like LIGO come online, scientists will be able to better probe the structure of space-time and understand the role of the cosmological constant in describing dark energy. Gravitational waves originating from the early universe may also provide insights into the moments after the big bang that cannot be studied using traditional telescopes since the light from that time would have been absorbed by hot plasma. Perhaps the most exciting glimpses that this new window into the universe will give us will be so unexpected that it will revolutionize our understanding of physics and astronomy.

large-scale structure The distribution of clusters and superclusters of galaxies in filaments and walls enclosing voids.

The Origin of Structure

On the largest scales, the universe is isotropic, meaning it looks the same in all directions. On smaller scales, there are irregularities. Galaxies are grouped in clusters ranging from a few galaxies to thousands, and those clusters appear to be grouped into superclusters. The Local Supercluster in which we live is a roughly disk-shaped swarm of galaxy clusters 160 to 245 million light-years in diameter. By measuring the redshifts and positions of thousands of galaxies in great slices across the sky, astronomers have been able to create maps revealing that the superclusters are not scattered at random. They are distributed in long, narrow filaments and thin walls that outline great voids nearly empty of galaxies (see Figure 11.17). These aggregations and gaps are referred to as **large-scale structure**.

This large-scale structure is a problem because the cosmic microwave background radiation is uniform, and that means the gas of the big bang must have been extremely uniform at the time of recombination. Yet the look-back time to the farthest known galaxy clusters, galaxies, and quasars is about 95 percent of the way back to the big bang. How did the uniform gas at the time of recombination



M. Blanton and the SDSS Collaboration, www.SDSS.org.

Figure 11.17 Nearly 70 000 galaxies are plotted in this double slice of the universe. The nearest galaxies are shown in red and the more distant in green and blue. The Sloan Great Wall is almost 1.4 billion light-years long and is the largest known structure in the universe.

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coagulate so quickly to form galaxy clusters, galaxies, and supermassive black holes in the centres of galaxies so early in the history of the universe? The answer appears to lie in the characteristics of dark matter.

Baryonic matter is so rare in the universe that it did not have enough gravity to pull itself together quickly after the big bang. As you learned earlier, astronomers propose that dark matter is nonbaryonic and therefore immune to the smoothing effect of the intense radiation that prevented normal matter from contracting. Dark matter was able to collapse into clouds and then pull in the normal matter to begin the formation of galaxies, clusters, and superclusters. Mathematical models, such as the one shown in Figure 11.18, attempt to describe this process, and cold dark matter does seem capable of jump-starting the formation of structure.

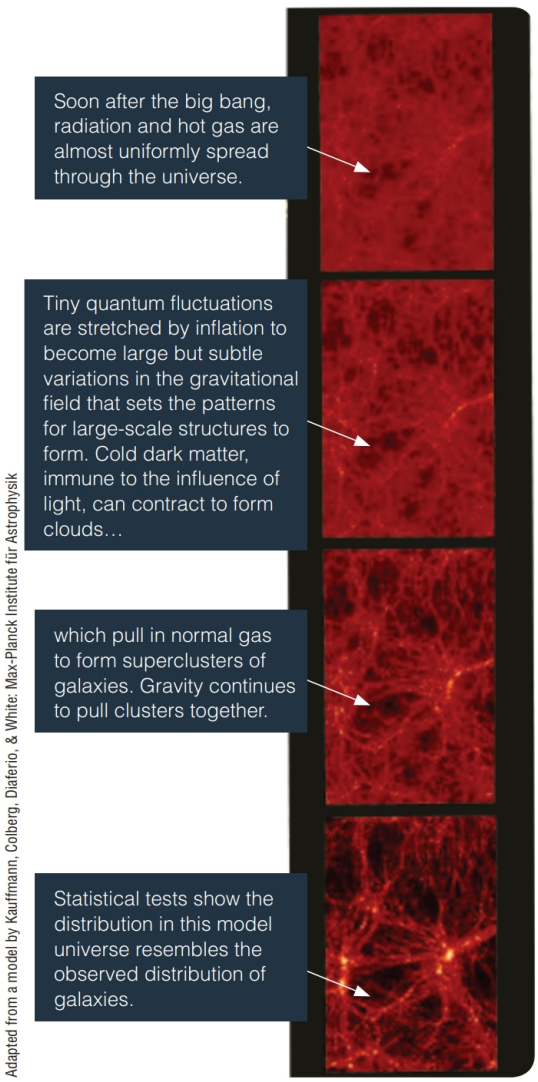


Figure 11.18 Mathematical model of the growth of structure in the universe.

But what started the clumping of the dark matter? Theorists say that space is filled with tiny, random quantum mechanical fluctuations smaller than the smallest atomic particles. At the moment of inflation, those tiny fluctuations would have been stretched to become very large, but very subtle, variations in gravitational fields, which could have later led to the formation of clusters, filaments, and walls. The structure you saw in Figure 11.17 may be the ghostly traces of quantum fluctuations in the infant universe.

CMB Irregularities and the Curvature of Space-Time

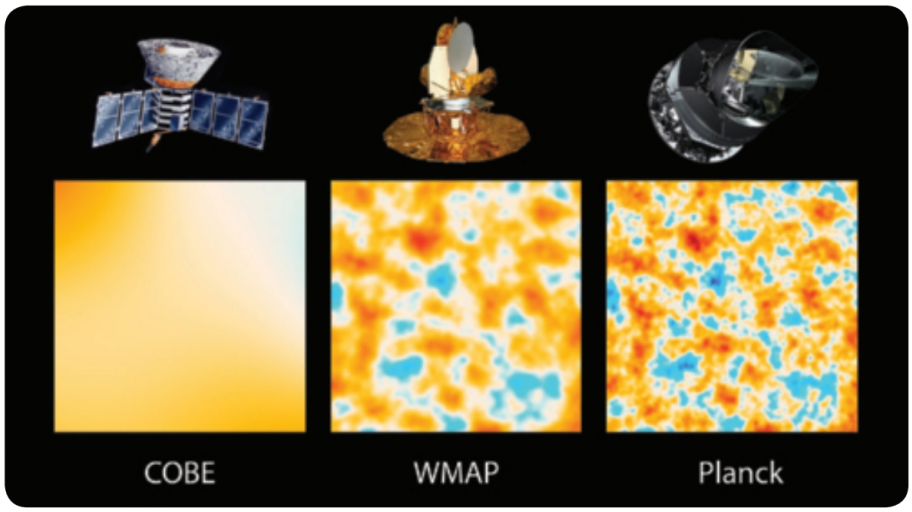
Observations of tiny irregularities in the background radiation can also reveal details about inflation and acceleration. In fact, the inflationary theory of the universe makes very specific predictions about the sizes of the irregularities an observer on Earth should see in the CMB.

The cosmic background radiation is highly isotropic; it looks almost exactly the same in all directions. However, when the average intensity is subtracted from each spot on the sky, small irregularities are evident. That is, some spots on the sky look a tiny bit hotter and brighter than other spots. In 1992, data from the Cosmic Background Explorer (COBE) space mission showed evidence of this anisotropy, and in 2006, George Smoot and John Mather won the Nobel Prize for their work on the COBE analysis. The Wilkinson Microwave Anisotropy Probe (WMAP), a space infrared telescope, has made further extensive observations of the type required to test predictions of CMB irregularities (see Figure 11.6). More recently, the European Space Agency's Planck space telescope has made the most accurate observations of the cosmic microwave background to date (Figure 11.19).

Cosmologists can analyze those irregularities in the intensity of the CMB by using sophisticated mathematics to measure how often spots of different sizes occur. The analysis confirms that spots about 1 degree in diameter are the most common, but spots of other sizes occur as well. A graph such as shown in Figure 11.20 can be plotted to show the irregularities of various sizes and how common these are.

Theory predicts that most of the irregularities in the hot gas of the big bang should be about 1 degree in diameter if the universe is flat. If the universe were

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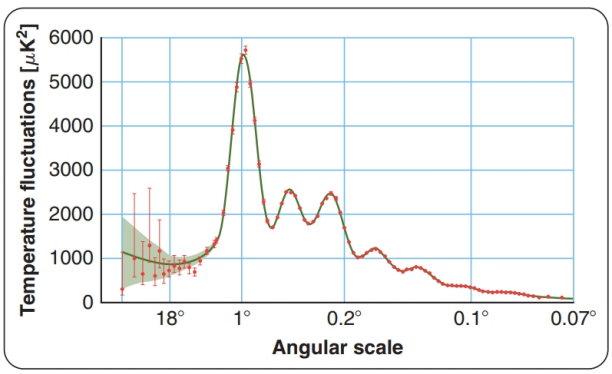


NASA/JPL-Caltech/ESA

Figure 11.19 The COBE, WMAP, and Planck missions measured the tiny temperature differences in the cosmic microwave background radiation with ever-increasing resolution. The three panels show the CMB variations in a region of the sky of area 10 square degrees. The CMB variations can be used to understand the composition, geometry, and age of the universe.

open, the most common irregularities would be smaller. The size of the irregularities in the cosmic background radiation show that the observations fit the flat universe model well, as you can see in Figure 11.20. You learned earlier in this chapter that a flat universe is most easily explained by inflation. Not only is the theory of inflation supported—an exciting result itself—but these data show that the universe is flat, which indirectly confirms the existence of dark energy and the acceleration of the universe.

The results from the WMAP and Planck observations make a complicated curve in Figure 11.20, and details of the wiggles tell cosmologists a great deal about the universe. The curve shows that the universe is flat, accelerating, and will expand forever. The age of the universe derived from the data is 13.8 billion years. Furthermore, the smaller peaks in the curve reveal that the universe contains 4.9 percent baryonic (normal) matter, 26.8 percent dark matter, and 68.3 percent dark energy. The Hubble constant is calculated to be 67.3 km/s/Mpc. The inflationary theory is confirmed, and the data support the cosmological constant version of dark energy, although quintessence is not quite ruled out. The dark matter needs to be "cold" (meaning, in this context, slow-moving) in order for it to clump together rapidly enough after the big bang to make the first galaxies, quasars, and galaxy clusters.



ESA and the Planck Collaboration. CC BY-SA 3.0 IGO (adapted)

Figure 11.20 This graph shows how commonly the irregularities of different sizes occur in the cosmic microwave background radiation. Irregularities of about 1 degree in diameter are most common. Models of the universe that are open or closed are ruled out. The data fit a flat model of the universe very well. Crosses on data points show the uncertainty in the measurements.

Please reread the preceding paragraph. What it says is truly amazing. WMAP, Planck, and other studies of the cosmic microwave background radiation and the distribution of galaxies have revolutionized cosmology. At last, astronomers have accurate observations against which to test theories. The basic constants are known to a precision of a few percent.

On reviewing these results, one cosmologist announced, "Cosmology is solved!" But that might be premature. The latest data from the Planck mission shows anomalies in the large scale structure of the cosmic microwave background that cannot be explained by our current models of cosmology. Scientists also don't understand dark matter or the dark energy that drives the acceleration, so over 95 percent of the universe is not understood. Hearing this, another astronomer suggested that a better phrase is "Cosmology is in crisis!" Certainly there are further mysteries to be explored, but cosmologists are growing more confident that they can describe the origin and evolution of the universe.

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The **Big Picture**

You have traced the origin of the universe, the creation of the chemical elements, the birth of galaxies, and the births and deaths of stars. You now have a perspective that few humans share, and you have tried to tackle some of the biggest and most difficult ideas in science.

As you review the history and structure of the universe, it is wise to recognize the mysteries that remain—but note that they are mysteries that may be solved and not mysteries that are unknowable. Only a century ago, humanity didn't know there were other galaxies, or that the universe was expanding, or that stars generate energy by nuclear fusion. Human curiosity has solved many of the mysteries of cosmology and will solve more during your lifetime.

Review and **Discussion Questions**

Review Questions

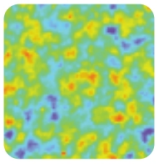
1. How does the darkness of the night sky tell you something important about the universe?
2. Why can't the universe have a centre?
3. What evidence shows that the universe is expanding? What evidence shows that it began with a big bang?
4. Why couldn't atomic nuclei exist when the age of the universe was less than two minutes?
5. Why are measurements of the present density of the universe important?
6. How does the inflationary universe theory resolve the flatness problem? How does it resolve the horizon problem?
7. If the Hubble constant were really 100 instead of 67.3 km/s/Mpc, much of what astronomers understand about the evolution of stars and star clusters would have to be wrong. Explain why. (*Hint*: What would the age of the universe be?)
8. What is the evidence that the universe was very uniform during its first 400 000 years?
9. What evidence can you cite that the expansion of the universe is accelerating?
10. What evidence can you cite that the universe is flat?

Discussion Questions

1. Do you think Copernicus would have accepted the cosmological principle? Why or why not?
2. If you reject any model of the universe that has an edge in space because you can't comprehend such a thing, shouldn't you also reject any model of the universe that has a beginning? Isn't a beginning like an "edge" in time, or is there a difference?

Learning to Look

1. The image below shows irregularities in the background radiation. Why isn't the background radiation perfectly uniform? What does the size of these irregularities tell you?



Courtesy of the Boomerang Collaboration

STUDY **TOOLS**

IN THE BOOK

- Tear Out the Review Card on *Life on Other Worlds*.

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
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Courtesy Dr. Burcin Mutlu-Pakdil

ESA/Hubble & NASA, CC BY-SA 3.0 IGO

AMONG THE TRILLIONS OF GALAXIES in the observable universe, the galaxy known as PGC 1000714 is unique. When it was studied in 2017, it was initially thought to be a type of galaxy called a Hoag-type galaxy. These rare galaxies have a central core and an outer ring of stars. Fewer than 0.1% of all galaxies are estimated to be of this type. But PGC 1000714 is even more unusual—it has not one but two almost circular rings. The stars of the outer ring are younger than the central elliptical galaxy, but the age of the fainter inner ring is yet to be determined. The origin and formation process of this peculiar galaxy is still unknown. It is nicknamed Burçin's galaxy after astrophysicist Burçin Mutlu-Pakdil, who led the study that identified its unique structure. Born and raised in Turkey, Dr. Mutlu-Pakdil is a postdoctoral researcher at the University of Arizona, studying dark matter in the faintest galaxies in the universe.

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PART FOUR

12 Planet Formation and Exoplanets

CHAPTER OUTLINE

12.1 The Great Chain of Origins
12.2 A Survey of the Planets
12.3 Space Debris: Asteroids, Comets, and Meteoroids
12.4 The Story of Planet Formation
12.5 Planet-Forming Disks Around Young Stars
12.6 Exoplanets: Planets Orbiting Other Stars

GUIDEPOST

In this vast universe, our local neighbourhood consists of our Sun and the planets, moons, asteroids, and comets of our solar system. The solar system is our home in the universe. Because humans are an intelligent species, we have the ability and the responsibility to wonder what we are. Our kind has inhabited this solar system for several million years, but only within the past hundred years have we begun to understand what a solar system is. To understand our place in the universe, we will explore the origins of the solar system and find answers to four important questions:

- What are the observed properties of the solar system as a whole?
- How did the solar system form?
- How do planets form?
- What do astronomers know about other planetary systems?

One reason to learn about the origin of the solar system is that we live here, but there is another reason. In the next two chapters you will explore each of the planets in more detail. By studying the origin of the solar system before studying individual planets, you will have a framework for understanding these fascinating worlds as well as for studying other planetary systems in the universe.



ESA, NASA, and L. Calcada (ESO for STScI)

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When you look at the stars and the galaxy, you feel that you are not just from any particular piece of land, but from the solar system.

Kalpana Chawla,
Indian-American NASA astronaut

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12.1 The Great Chain of Origins

You are linked through a great chain of origins that leads back in time to the first instant when the universe began 13.8 billion years ago. The gradual discovery of the links in that chain is one of the most exciting adventures of the human intellect. In earlier chapters, you studied some of that story: the origin of the universe in the big bang, the formation of galaxies, the origin of stars, and the production of the chemical elements. Here you will explore further and consider the origin of planets.

The History of the Atoms in Your Body

By the time the universe was a few minutes old, the protons, neutrons, and electrons in your body had come into existence (see Chapter 11). You are made of very old matter.

Although those particles formed quickly, they were not linked together to form the atoms that are common today. Most of the matter was hydrogen, and about 25 percent of it was helium. Very few of the heavier atoms were made in the big bang. Although your body does not contain helium, it does contain many of those ancient hydrogen atoms unchanged since the universe began.

Within a few hundred million years after the big bang, matter began to collect to form galaxies containing billions of stars. You have learned how nuclear reactions inside stars combine low-mass atoms such as hydrogen to make heavier atoms. Generations of stars cooked the original particles, fusing them into atoms such as carbon, nitrogen, and oxygen (see Chapters 8 and 9). Those are common atoms in your body. Even the calcium atoms in your bones were assembled inside stars.

Most of the iron in your body was produced by carbon fusion in type Ia supernovae and by the decay of radioactive atoms in the expanding matter ejected by type II supernovae. Some atoms heavier than iron (for example iodine, critical in the functioning of your thyroid gland), were created by rapid nuclear reactions that can occur during supernova explosions (see Chapter 8). Elements uncommon enough to be expensive, such as the gold, silver, and platinum in jewellery, were also produced during the violent deaths of rare massive stars.

solar nebula theory A theory of formation of the solar system consistent with our current observations that describes how a rotating cloud of gas and dust gravitationally collapsed and flattened into a disk with the Sun forming at the centre, and the planets forming around it.

Our galaxy contains at least 100 billion stars, including the Sun. It formed from a cloud of gas and dust about 5 billion years ago, and the atoms in your body were part of that cloud. How the Sun took shape, how the cloud gave birth to the planets, how the atoms in your body found their way onto Earth and into you is the story of this chapter. As you explore the origin of the solar system, keep in mind the great chain of origins that created the atoms. As the geologist Preston Cloud remarked, "Stars have died that we might live."

The Origin of the Solar System

Astronomers have a theory for the origin of our solar system that best fits our latest observations of the solar system and with observations of star formation, and now they are refining the details.

The **solar nebula theory** proposes that planets form in rotating disks of gas and dust around young stars (Figure 12.1). These young stars form at the centre of a rotating cloud of gas and dust that starts to contract due to

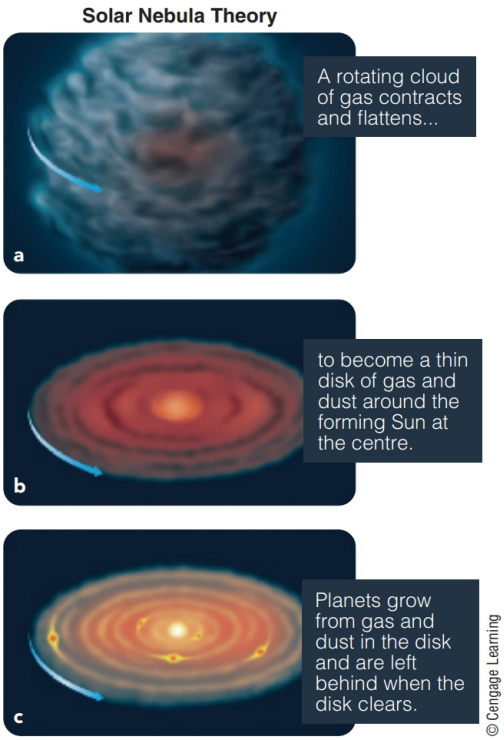
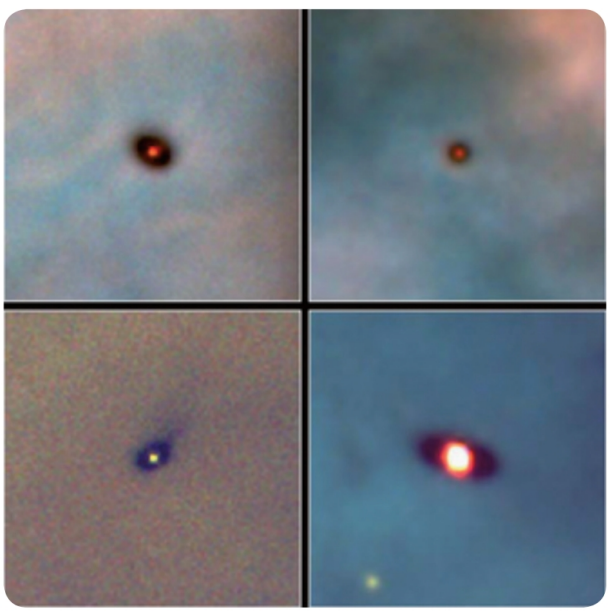


Figure 12.1 The solar nebula theory. (a) A rotating cloud of gas contracts and flattens. (b) The cloud of gas forms a thin disk of gas and dust around the Sun forming at the centre. (c) Planets grow from gas and dust in the disk and remain in orbit due to the Sun's gravity.

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gravity. Collisions between particles in the rotating cloud tend to flatten the cloud into a disk shape. In addition, as the cloud shrinks it spins faster due to the conservation of angular momentum. Most of the material in the spinning disk forms a star in the centre, while the remaining material forms the planets and other bodies such as asteroids and comets. There is now clear evidence that disks of gas and dust are common around young stars. This idea is so comprehensive and explains so many observations that it can be considered to have "graduated" from being just a hypothesis to being properly called an evidence-based scientific theory. Bipolar flows from protostars were the first evidence of such disks, but modern techniques, like those used by the Hubble telescope in Figure 12.2, can image the disks directly. Our own planetary system formed in such a disk-shaped cloud around the Sun. When the Sun became luminous enough, the remaining gas and dust were blown away into space by the solar wind (a stream of charged particles from the Sun), leaving the planets orbiting the Sun.

According to the solar nebula theory, Earth and the other planets of our solar system formed billions of years ago as the Sun condensed from the interstellar medium. One reason that scientists form theories about a particular physical system (such as our Sun and its planets) is to be able to use the theory to make predictions about other similar systems (such as other star systems). The solar nebula theory allows scientists to make a powerful prediction about planet formation. This theory predicts that most stars should have planets because planet formation is a natural part of star formation, and therefore planets should be very common in the universe, probably more common than stars.



© Corbis

Figure 12.2 Dust and gas disks around young stars are evident in these Hubble telescope images of the Orion Nebula.

12.2 A Survey of the Planets

To confirm the solar nebula theory, and to explore its consequences, astronomers search the present solar system for evidence of its past. The next two sections provide a survey of the solar system and a list of its most significant characteristics, which are potential clues to how it formed.

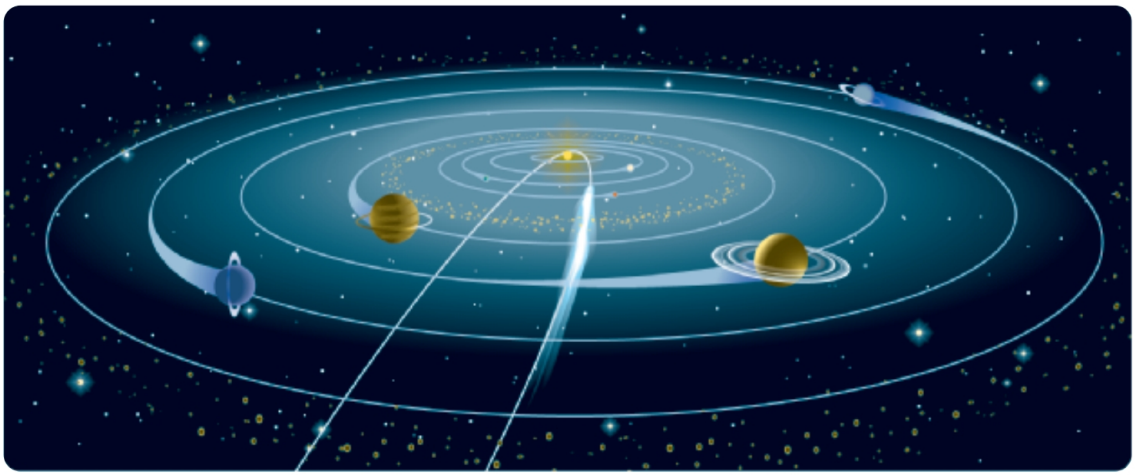
Begin with the most general view of the solar system. It is, in fact, almost entirely empty space (refer to **Visualizing Astronomy 1.1, The Scale of the Very Small and Very Large: Powers of 10**). Imagine that you reduce the solar system until Earth is the size of a small grain of table salt, about 0.3 mm in diameter. The Sun is the size of a small plum 4 m from Earth. Jupiter is an apple seed 20 m from the Sun. Neptune, at the edge of the solar system, is a large grain of sand located 120 m from the central plum. You can see from this scaled down model that planets are tiny specks of matter scattered around the Sun; they are the last significant remains of the solar nebula.

Revolution and Rotation

The planets revolve around the Sun in orbits that lie close to a common plane (Figure 12.3). Recall from Chapter 2 that the words *revolve* and *rotate* refer to different motions; a planet revolves around the Sun but rotates on its axis. Mercury, the closest planet to the Sun, has an orbit around the Sun that is tipped 7.0° to Earth's orbit. The rest of the planets' orbital planes are inclined by no more than 3.4°. The solar system is basically "flat" and disk shaped.

The rotation of the Sun and planets on their axes also seems related to the same overall direction of motion. The Sun rotates with its equator inclined only 7.2° to Earth's orbit, and most of the other planets' equators are tipped less than 30°. However, the rotations of Venus and Uranus are peculiar. Venus rotates backward compared to the other planets, and Uranus rotates on its "side" (with its equator almost perpendicular to its orbit). Later in this chapter you will learn a hypothesis about how these planets may have acquired their peculiar rotations.

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Figure 12.3 All the planets in our solar system orbit in the same direction; all their orbits lie roughly in one plane. Comets, however, have orbits that are often inclined out of the plane of the planetary orbits. These are all clues to how the solar system formed. At the scale of this image, the planets are actually roughly 2000 times smaller in diameter than what is shown here. They have been drawn larger for viewing convenience.

asteroid Small, rocky world. Most orbit between Mars and Jupiter in the asteroid belt.

Apparently, the preferred direction of motion in the solar system—counter-clockwise as seen from the north—is related to the rotation of the disk of material that became the planets. All the planets revolve around the Sun in that direction, and with the exception of Venus and Uranus, they rotate on their axes in that same direction. Furthermore, nearly all the moons in the solar system, including Earth's moon, orbit around their planets in that direction. With only a few exceptions, most of which astronomers think they understand, revolution and rotation in the solar system both follow a common direction.

Two Kinds of Planets

Perhaps the most striking clue to the origin of the solar system comes from the obvious division of the planets into two categories: the small Earth-like worlds and the giant Jupiter-like worlds. The difference is so dramatic that you are led to say, "Aha, this must mean something!" Study **Visualizing Astronomy 12.1, Terrestrial and Jovian Planets,** and notice three important points:

1. The two kinds of planets are distinguished by their location. The four inner (Terrestrial) planets are quite different from the four outer (Jovian) planets.
2. Almost every solid surface in the solar system is covered with craters.
3. The two groups of planets are also distinguished by properties such as composition, rings, and moons. Any theory of the origin of planets needs to explain these properties.

The division of the planets into two families is a clue to how our solar system formed. However, the present properties of individual planets do not tell you everything you need to know about their origins. The planets have all evolved since they formed. For further clues you can look at smaller objects that have remained largely unchanged since the birth of the solar system.

12.3 Space Debris: Asteroids, Comets, and Meteoroids

The Sun and planets are not the only remains of the solar nebula. The solar system is littered with three kinds of space debris: asteroids, comets, and meteoroids. Although these objects represent a tiny fraction of the mass of the system, they are a rich source of information about the origin of the planets.

Asteroids

The **asteroids**, sometimes called minor planets, are small rocky worlds, most but not all of which orbit the Sun in a belt between the orbits of Mars and Jupiter. More than 100 000 asteroids have orbits that are charted, of which at least 2000 follow orbits that bring them into the inner solar system where they can occasionally collide with a planet; in fact, Earth has been struck many times in its history. Some asteroids share Jupiter's orbit, and others have been found beyond the orbit of Saturn.

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About 200 asteroids are more than 100 km in diameter, and tens of thousands are estimated to be more than 10 km in diameter. There are probably a million or more that are larger than 1 km and billions that are smaller. Because even the largest are only a few hundred kilometres in diameter, Earth-based telescopes are not powerful enough to detect details on their surfaces, and even the Hubble Space Telescope can image only the largest features.

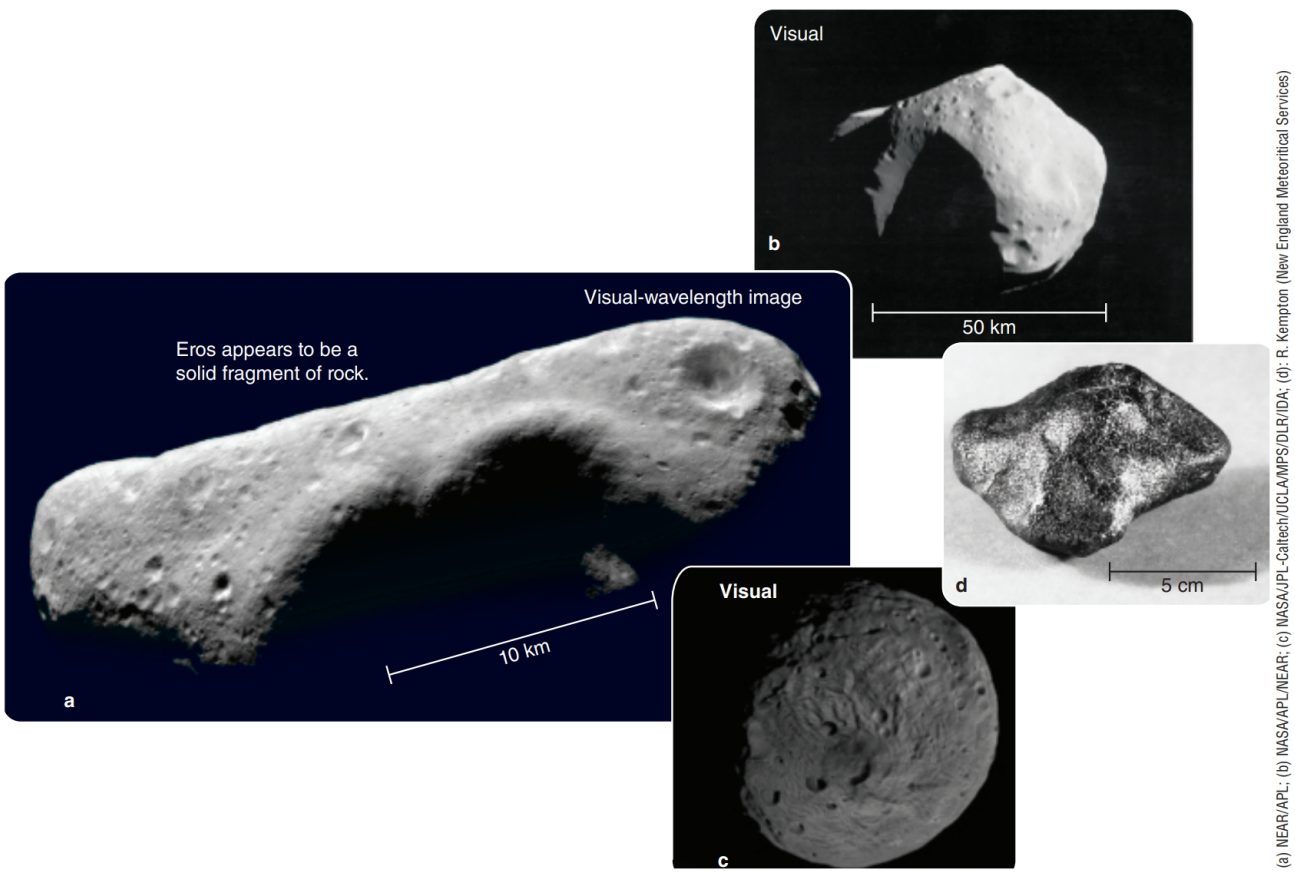
Photographs returned by robotic spacecraft and space telescopes show that asteroids are generally irregular in shape and battered by impact cratering (Figure 12.4). In fact, some asteroids appear to be piles of broken fragments clumped together by gravity, and a few asteroids are known to be double objects or to have small moons in orbit around them. These are understood by astronomers to be evidence of multiple collisions among the asteroids. A few larger asteroids show signs of volcanic activity on their surfaces that may have happened when those asteroids were young.

Astronomers recognize the asteroids as debris left over during planet formation at a distance of about 3 AU from the Sun. A good theory should be able to explain why a planet didn't form there but instead left behind a belt of construction material.

Comets

In contrast to the rocky asteroids, the brightest **comets** are impressively beautiful objects (see Figure 12.5). Most comets are faint, however, and difficult to locate even at their brightest. Comets also orbit the Sun, but a comet may take months to sweep through the inner solar system, during which time it appears as a glowing head with an extended tail of gas and dust.

comet One of the small, icy bodies that orbit the Sun and produce tails of gas and dust when they approach the Sun.



(a) NEAR/APL; (b) NASA/APL/NEAR; (c) NASA/JPL-Caltech/UCLA/MPS/DLR/IDA; (d): R. Kempton (New England Meteoritical Services)

Figure 12.4 (a) The Near Earth Asteroid Rendezvous (*NEAR*) spacecraft visited the asteroid Eros in 2000 and found it heavily cratered by collisions and covered by a layer of crushed rock and dust. (b) The asteroid Mathilde, photographed by the *NEAR* spacecraft during a flyby, has a very low density, similar to other known asteroids that may be rubble piles with large empty spaces between solid fragments. (c) The large asteroid Vesta has a spectrum resembling solidified lava. Vesta seems to have had internal heat and volcanic activity in its past, perhaps due to decay of radioactive minerals. This image of the asteroid Vesta, taken from a distance of 2700 km by NASA's *Dawn* spacecraft, shows Vesta's south polar region, which is dominated by the Rheasilvia impact basin. (d) One class of meteorites that is spectroscopically identical to Vesta is made of basalt, a volcanic rock.

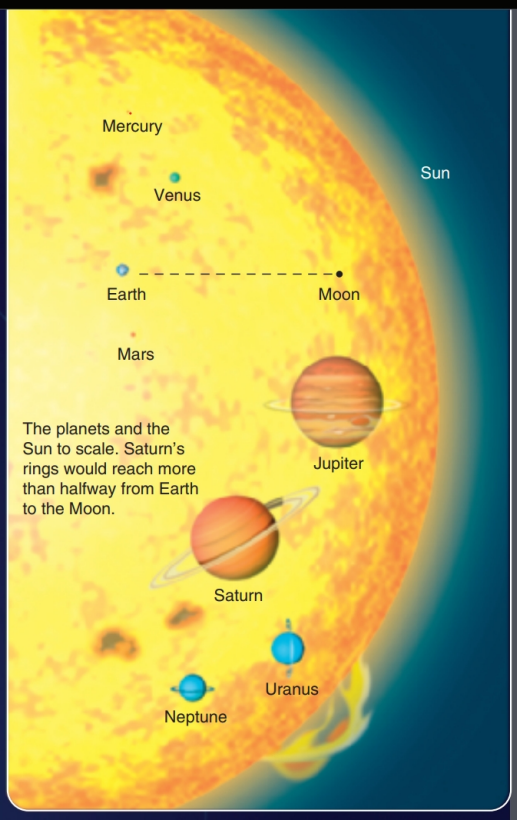
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Visualizing Astronomy 12.1

TERRESTRIAL AND JOVIAN PLANETS

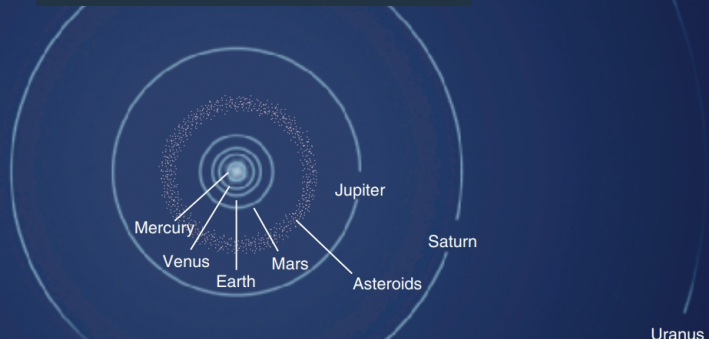
1

The distinction between the Terrestrial planets and the Jovian planets is dramatic. The inner four planets, Mercury, Venus, Earth, and Mars, are **Terrestrial planets**, meaning they are small, dense, rocky worlds. The outer four planets, Jupiter, Saturn, Uranus, and Neptune, are **Jovian planets**, meaning they are large, low-density worlds with thick atmospheres and liquid or ice interiors.



The planets and the Sun to scale. Saturn's rings would reach more than halfway from Earth to the Moon.

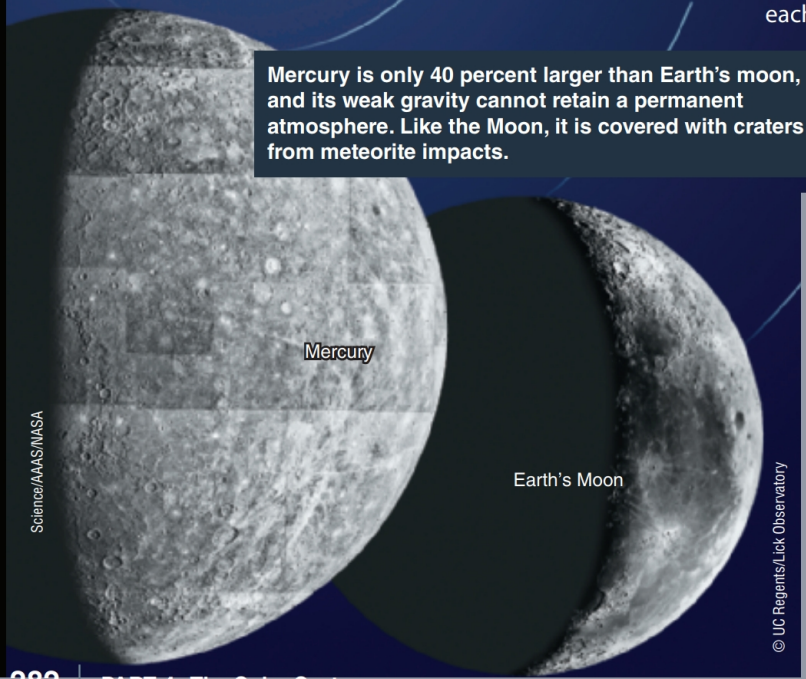
Planetary orbits to scale. The Terrestrial planets lie close to the Sun, whereas the Jovian planets are spread far from the Sun.



1a

Of the Terrestrial planets, Earth is the most massive, but the Jovian planets are much more massive. Jupiter contains over 300 Earth masses, Saturn nearly 100 Earth masses. Uranus and Neptune each contain about 15 Earth masses.

Mercury is only 40 percent larger than Earth's moon, and its weak gravity cannot retain a permanent atmosphere. Like the Moon, it is covered with craters from meteorite impacts.



Science/AAAS/NASA

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2

Craters are common on all of the surfaces in the solar system that are strong enough to retain them. Earth has about 150 impact craters, but many more have been erased by erosion. Terrestrial planets, asteroids, comet nuclei, and nearly all of the moons in the solar system are scarred by craters. Ranging from microscopic to hundreds of kilometres in diameter, these craters have been produced over the ages by meteorite impacts. When astronomers see a rocky or icy surface that contains few craters, they know that the surface is young.

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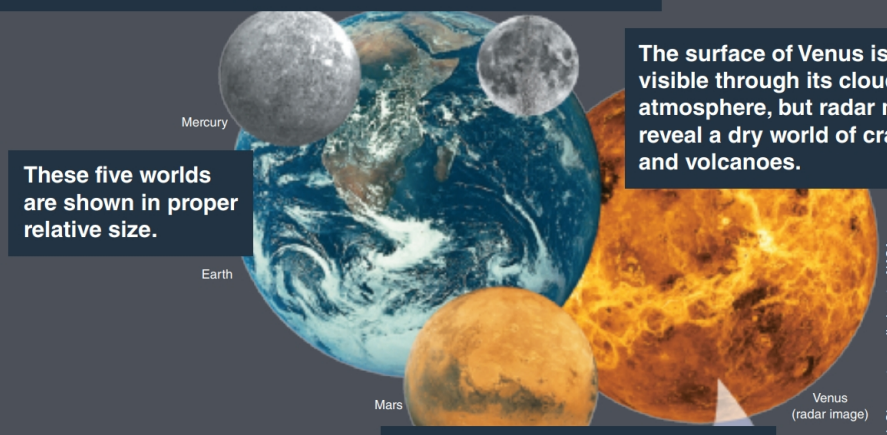
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3 The Terrestrial planets have densities like that of rock or metal. The Jovian planets all have low densities, and Saturn's average density is only about 70 percent that of water. It would float in a big-enough bathtub.

The atmospheres of the Jovian planets are turbulent, and some are marked by great storms such as the Great Red Spot on Jupiter, but the atmospheres are not deep. If Jupiter were shrunk to the size of a tennis ball, its atmosphere would be no deeper than the fuzz.

Mercury is so close to the Sun it is difficult to study from Earth. The *MESSENGER* spacecraft went into orbit around Mercury in 2011 and was able to take detailed photos of the planet's entire surface.

3a The interiors of the Jovian planets contain small cores of heavy elements such as metals, surrounded by a liquid. Jupiter and Saturn contain hydrogen forced into a liquid state by the high pressure. Less-massive Uranus and Neptune contain heavy-element cores surrounded by partially solid water mixed with heavy material such as rocks and methane ices.



These five worlds are shown in proper relative size.

The surface of Venus is not visible through its cloudy atmosphere, but radar maps reveal a dry world of craters and volcanoes.

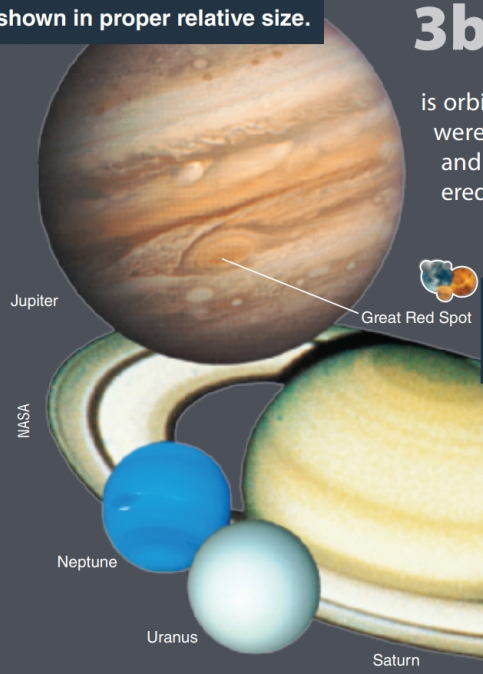
© UC Regents/Lick Observatory; all planets, NASA

Mars has a thin atmosphere and little water. Craters and volcanoes are common on its desert surface.



These Jovian worlds are shown in proper relative size.

3b The Jovian planets have extensive systems of satellites. For example, Jupiter is orbited by four large moons which were discovered by Galileo in 1610, and dozens of smaller moons discovered up to the present day.



The Terrestrial planets are drawn here to the same scale as the Jovian planets.



3c All four Jovian planets have ring systems. Saturn's rings are made of ice particles. The rings of Jupiter, Uranus, and Neptune are made of dark rocky particles. Terrestrial planets have no rings.

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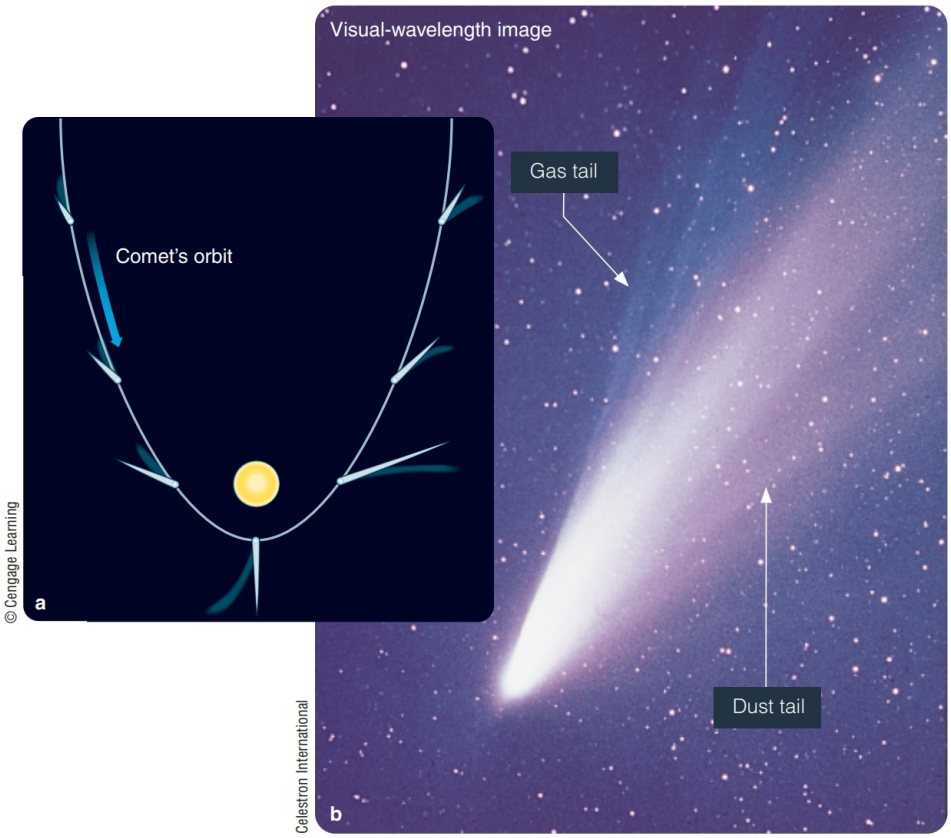


Figure 12.5 (a) A comet in a long, elliptical orbit becomes visible when the Sun's heat vaporizes its ices and pushes the gas and dust away in separate tails. (b) A comet may remain visible in the evening or morning sky for weeks as it moves through the inner solar system. Comet West was in the sky during March 1976.

The beautiful tail of a comet can be longer than an AU, but it is produced by an icy nucleus (sometimes described as a dirty snowball) only a few tens of kilometres in diameter. The nucleus remains frozen and inactive while the comet is far from the Sun. As the nucleus moves along its elliptical orbit into the inner solar system, the Sun's heat begins to vaporize the ices, releasing gas and dust. The pressure of sunlight and the solar wind pushes the gas and dust away, forming a long tail. The gas and dust respond differently to the forces acting on them, so they sometimes separate into two separate sub-tails (Figure 12.5a). The solar wind pushes the gas tail to point directly away from the Sun, whereas the motion of the nucleus along its orbit and the pressure of sunlight cause the dust tail to point approximately away from the Sun (Figure 12.5b).

volatile Easily evaporated.

Kuiper belt The collection of icy planetesimals orbiting in a region from just beyond Neptune out to 50 AU or more.

Oort cloud The hypothetical source of comets, a swarm of icy bodies understood to lie in a spherical shell extending to 100 000 AU from the Sun.

Comet nuclei contain ices of water and other **volatile** (easily vaporized) compounds, such as carbon dioxide, carbon monoxide, methane, and ammonia. These ices are the kinds of compounds that should have condensed from the outer solar nebula, and that make astronomers think comets are ancient samples of the gases and dust from which the outer planets formed.

Five spacecraft flew past the nucleus of Comet Halley when it passed through the inner solar system in 1985 and 1986. Since then spacecraft have visited the nuclei of several other comets. Images show that comet nuclei are irregular in shape and very dark, with jets of gas and dust spewing from active regions on the nuclei. In general, these nuclei are darker than a lump of coal, which suggests their composition is similar to certain dark, water- and carbon-rich meteorites.

Since 1992, astronomers have discovered over 2000 small, dark, icy bodies orbiting in the outer fringes of the solar system beyond Neptune. This collection of objects is called the **Kuiper belt**, after the Dutch-American astronomer Gerard Kuiper (pronounced coy-per), who predicted their existence in the 1950s. Some Kuiper belt objects are quite large. Eris is in fact larger than Pluto. Other large bodies include Sedna and Orcus. You will learn more about Pluto and its connection to the Kuiper belt in Chapter 13. There are probably hundreds of thousands of bodies larger than 100 km in the Kuiper belt, and any successful theory should explain how they came to be where they are. Astronomers have evidence that some comets—those that move in the plane of the solar system with relatively short orbital periods—come from the Kuiper belt.

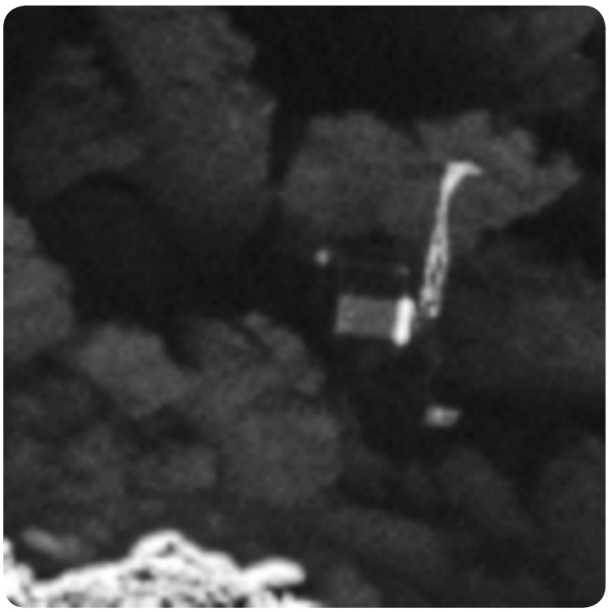
The longer-period comets do not always orbit in the plane of the solar system, but can approach the Sun from random directions. They are believed to originate from the **Oort cloud**, a roughly spherical cloud of comets that is believed to lie much farther away at a

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distance of about 1 light-year from the Sun. The Oort cloud is named after the Dutch astronomer Jan Oort, who first suggested its existence in 1950. Trillions of objects larger than 1 km in size are estimated to lie in the Oort cloud. The edge of the Oort cloud forms the outer boundary of our solar system. You will understand how the solar nebula theory can explain these two different sources of comets.

Numerous unmanned spacecraft have been launched to study asteroids and comets. The *International Cometary Explorer* (ICE) spacecraft, jointly operated by NASA and the European Space Agency (ESA), performed the first flyby of a comet when it flew through the tail of comet Giacobini-Zinner in 1978. Halley's Comet, which can be seen from Earth every 75 years, was the subject of a flyby mission by Japan's *Sakigake* spacecraft in 1985. NASA's *Galileo* performed the first asteroid flyby in 1985 and also discovered the first asteroid moon, Dactyl. It was not until 2000 that the spacecraft *NEAR Shoemaker* performed the first asteroid landing by touching down on the asteroid Eros. In 1999, the spacecraft *Stardust* collected samples from the coma of the comet Wild 2, and the sample capsules successfully returned to Earth. The Japanese *Hayabusa* asteroid lander became the first to return samples from an asteroid in 2003. *Deep Impact* was launched in 2005 to send an impactor to collide with a comet in order to study the interior of the comet. The mission showed that the comet was less icy and more dusty than expected. The probe *Dawn* was launched in 2007 to study the massive asteroids Vesta and Ceres. It orbited Vesta in 2011 before continuing toward Ceres, where it will remain in orbit for centuries, although it ended mission communications in 2018. The data from *Dawn* will give scientists insights into the origins of the solar system. The China National Space Administration (CNSA) became the fourth space agency to explore an asteroid with its *Chang'e 2* probe in 2012. In 2014, the world watched in wonder as the European Space Agency's *Rosetta* mission successfully landed a lander (*Philae*) on the comet 67P/Churyumov-Gerasimenko (Figure 12.6). And in 2019, the *New Horizons* probe, whose primary mission was a flyby of Pluto, also performed a flyby manoeuvre around a Kuiper belt object, Ultima Thule, before heading out of the solar system (see Chapter 14).

NASA's *OSIRIS Rex* probe is orbiting the asteroid 101955 Bennu, which may pose a threat to Earth in the future. The probe will return a sample of the asteroid to Earth in 2023. Japan's *Hyabusa 2*, launched in 2014, will create an impact crater on asteroid Ryugu to collect sample materials that will be returned to Earth in 2020. The ESA is planning a similar impactor mission to an asteroid to study whether this could be used to redirect an asteroid that may be on course to collide with Earth. As space agencies around the world continue their efforts to explore our solar system, you may one day hear about human beings landing on an asteroid or a comet.



ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA, CC BY-SA 3.0 IGO

Figure 12.6 The *Philae* lander landed on the comet 67P/Churyumov-Gerasimenko in 2014, marking the success of the European Space Agency's *Rosetta* mission.

Meteoroids, Meteors, Meteorites

Unlike the stately comets, **meteors** flash across the sky in momentary streaks of light. They are commonly called "shooting stars," but they are not stars. They are small bits of rock and metal falling into Earth's atmosphere and bursting into incandescent vapour about 80 km above the ground due to friction with the air. This vapour condenses to form dust, which settles slowly to the ground. Every year about 40 000 tons of this dust settles on Earth's surface.

Technically, the word *meteor* refers to the streak of light in the sky. In space, before its fiery plunge, the object is called a **meteoroid**. Most meteoroids are the size of dust, grains of sand, or tiny pebbles. Almost all the meteors you see in the sky are produced by meteoroids that weigh less than 1 gram. Only rarely is a meteoroid

meteor A small bit of matter heated by friction to incandescent vapour as it falls into Earth's atmosphere.

meteoroid A meteor in space before it enters Earth's atmosphere.

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meteorite A meteor that does not completely burn up during its passage through Earth's atmosphere and strikes the ground.

carbonaceous chondrite Stony meteorite that contains small, glassy spheres—called chondrules—and volatiles. These chondrites may be the least-altered remains of the solar nebula still present in the solar system.

meteor shower A display of meteors that appear to come from one point in the sky; understood to be cometary debris.

massive and strong enough to survive its plunge and reach Earth's surface. Such a rock is called a **meteorite**.

Meteorites can be divided into three broad categories. *Iron* meteorites are solid chunks of iron and nickel. *Stony* meteorites are silicate masses that resemble Earth rocks. *Stony-iron* meteorites are mixtures of iron and stone. These types of meteorites are illustrated in Figure 12.7.

One type of stony meteorite is called **carbonaceous chondrite**. These meteorites generally contain abundant volatile compounds, including significant amounts of carbon and water, and may have similar composition to comet nuclei. Heating would have modified and driven off these fragile compounds, so carbonaceous chondrites must not have been heated ever since they formed. Astronomers conclude that carbonaceous chondrites, unlike the planets, have not changed since they formed, so they give direct information about the early solar system.

You can see evidence of the origin of meteors by watching a **meteor shower**, a display of meteors that are clearly related by a common origin and one of the most pleasant observations in astronomy. For example, the Perseid meteor shower occurs each year in August, and during the height of the shower you might see as many as 40 meteors per hour. The Perseid shower is so named because all its meteors appear to come from a point in the constellation Perseus. Meteor showers are seen when Earth passes near the orbit of a comet (Figure 12.8). The Eta Aquariids meteor shower, best viewed from the southern hemisphere, is caused by Earth passing through dust released by Halley's Comet. The meteors in meteor showers must be produced by dust and debris released from the icy head of the comet. In contrast, the orbits of some meteorites have been calculated to lead back into the asteroid belt.



Lab photo, Russell Kempton, New England Meteoritical Services

Figure 12.7 Iron and stony meteorites have different structures.

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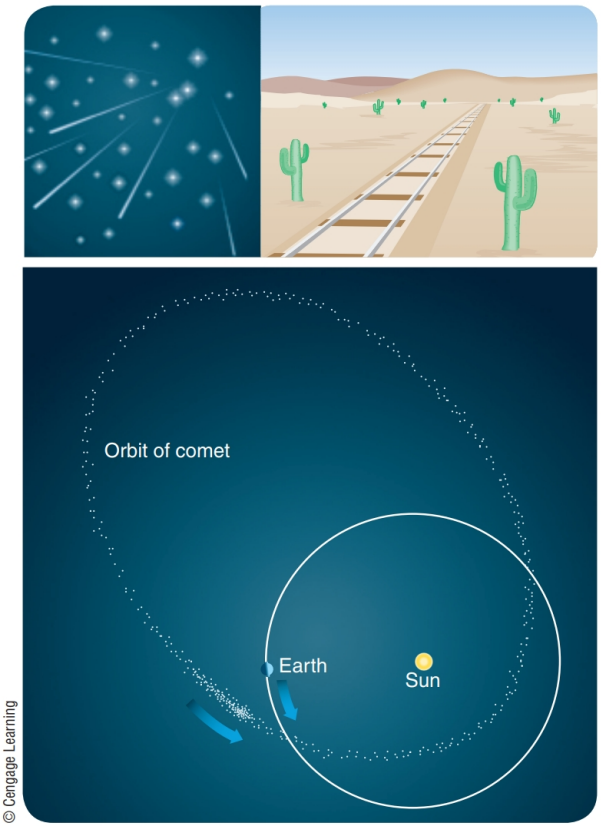


Figure 12.8 Meteors in a meteor shower enter Earth's atmosphere along parallel paths, but, much like lines on a road, perspective makes them appear to diverge from a radiant point in the sky. Meteors in a shower are debris left behind as a comet's icy nucleus vaporizes. The rocky and metallic bits of matter spread along the comet's orbit. If Earth passes through such material, you can see a meteor shower.

An important reason to mention meteorites here is for one specific clue they give concerning the solar nebula: Meteorites can reveal the age of the solar system.

12.4 The Story of Planet Formation

The challenge for modern planetary astronomers is to compare the characteristics of the solar system with the solar nebula theory and tell the story of how the planets formed.

The Age of the Solar System

According to the solar nebula theory, the planets should be about the same age as the Sun. The most accurate way to find the age of a rocky body is to bring a sample into the laboratory and determine its age by analyzing the radioactive elements it contains.

half-life The time required for half of the radioactive atoms in a sample to decay into lighter elements.

When a rock solidifies, the process of cooling causes it to incorporate known proportions of the chemical elements. A few of these elements are radioactive and decay into other lighter elements, called daughter elements or isotopes. The **half-life** of a radioactive element is the time it takes for half of the radioactive atoms to decay into the daughter elements. For example, potassium-40 decays with a half-life of 1.3 billion years into daughter isotopes calcium-40 and argon-40. Another example, uranium-238, decays with a half-life of 4.5 billion years into lead-206 and other isotopes. As time passes, the abundance of a radioactive element in a rock gradually decreases, and the abundances of the daughter elements gradually increase (Figure 12.9). You can estimate the original abundances of the elements in the rock from rules of chemistry and observations of rock properties in general. Thus, measuring the present abundances of the parent and daughter elements allows you to find the age of the rock. For example, suppose you find equal

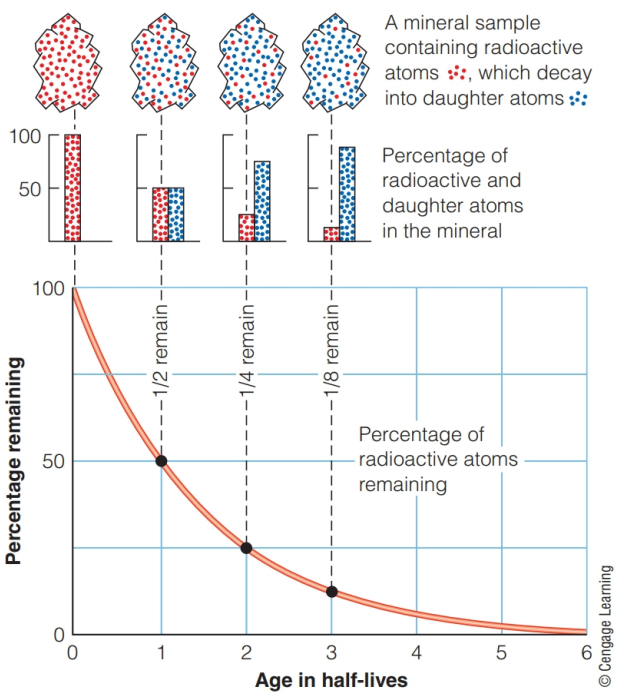


Figure 12.9 The radioactive atoms in a mineral sample (red) decay into daughter atoms (blue). Half the radioactive atoms are left after one half-life, a fourth after two half-lives, an eighth after three half-lives, and so on.

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proportions of uranium-238 and lead-206 in a rock sample. You know that the half-life of uranium-238 is 1.3 billion years, which means half the uranium atoms will have decayed into lead in this time. Hence you will know that the age of the rock is 1.3 billion years. In another 1.3 billion years, half of the remaining half of uranium atoms will also have decayed into lead. So if you find a rock with the proportion of uranium being one-quarter the proportion of lead, then you will know that two half-lives have passed and the rock is 2.6 billion years. This works best if you have several radioactive element "clocks" that can be used as independent checks on each other.

To determine a radioactive age you need a sample in the laboratory, and the only celestial bodies from which scientists have samples are Earth, the Moon, Mars, and meteorites. Tiny zircon crystals discovered in Australia have been dated to 4.4 billion years old. The oldest known rock on the planet was found in the Northwest Territories of Canada. It is 4 billion years old. The surface of Earth is active, and the crust is continually destroyed and reformed from material welling up from beneath the crust (see Chapter 13). Consequently, the age of these oldest rocks tells us only that Earth is *at least* 4.4 billion years old.

Unlike Earth's surface, the Moon's surface is not being recycled by constant geologic activity, so you can guess that more of it might have survived unaltered since early in the history of the solar system. The oldest rocks brought back from the Moon by the *Apollo* astronauts are 4.48 billion years old. That means the Moon must be at least 4.48 billion years old. Although no one has yet been to Mars, over a dozen meteorites found on Earth have been identified by their chemical composition as having come from Mars. The oldest has an age of approximately 4.5 billion years. Mars must be at least that old.

The most important source for determining the age of the solar system is meteorites (Figure 12.10). Recall that the composition of carbonaceous chondrite meteorites indicates that they have not been heated much or otherwise altered since they formed. They have a range of ages with a consistent and precise upper limit of 4.56 billion years. This number, often rounded to 4.6 billion years, is widely accepted as the age of the solar system. That is in agreement with the age of the Sun, which is estimated to be 5 billion years plus or minus 1.5 billion years: an estimate based on mathematical models of the Sun's interior (see Chapter 7) that are completely independent of meteorite radioactive ages.



University Relations-University of Alberta

Figure 12.10 On the morning of January 18, 2000, a huge fireball was observed over northwestern Canada as a 1.3-ton meteorite slammed into Tagish Lake, British Columbia. Within days, several fragments of the rock were recovered in an uncontaminated state, making these the most pristine rocks from the solar system ever recovered. The Tagish Lake meteorite is one of the most primitive types of meteorites and is thought to have remained more or less unchanged since the solar system first formed. Primitive organic molecules have been discovered in the fragments, and extraterrestrial ice may have been preserved in some of the frozen rocks. This gives scientists a unique opportunity to study conditions in the early solar system and the origins of life on Earth.

Apparently, all the bodies of the solar system formed at about the same time some 4.6 billion years ago. This is the final item on your list of characteristic properties of the solar system (Table 12.1). Each of these characteristics needs to be explained by a good theory of the formation of the solar system.

Table 12.1 Characteristic Properties of the Solar System

1.	Disk shape of the solar system Orbits in nearly the same plane Common direction of revolution and rotation
2.	Two planetary types Terrestrial—inner planets—small, high density Jovian—outer planets—large, low density
3.	Planetary rings and large satellite systems around the Jovian planets, not around the Terrestrial planets
4.	Space debris—asteroids, comets, and meteors Two types of composition—rocky and icy Two types of orbits—inner solar system and outer solar system
5.	Common age of about 4.6 billion years for Earth, the Moon, Mars, meteorites, and the Sun

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Chemical Composition of the Solar Nebula

Everything astronomers know about the solar system and star formation suggests that the solar nebula was a fragment of an interstellar gas cloud. Such a cloud would have been mostly hydrogen, with some helium and minor traces of the heavier elements.

This is precisely what you see in the composition of the Sun (refer to Table 5.1). Analysis of the solar spectrum shows that the Sun is mostly hydrogen, with a quarter of its mass being helium and only about 2 percent being heavier elements. Although solar nuclear reactions fuse some hydrogen into helium, this happens in the Sun's core and does not affect its surface composition. This means the composition of the Sun's atmosphere revealed in its spectrum is essentially the composition of the solar nebula gases from which it formed.

The same solar nebula composition is reflected in the chemical compositions of the planets. The composition of Jupiter and the other Jovian planets resembles the composition of the Sun. Furthermore, if low-density gases escaped from a blob of Sun-stuff, the remaining heavier elements would resemble the composition of Earth, the other Terrestrial planets, and meteorites.

Condensation of Solids

The key to understanding the process that converted the nebular gas into solid matter is the observed variation in density among solar system objects. Recall that the four inner planets are high-density Terrestrial bodies, and the outer, Jupiter-like planets are low-density, giant planets. This division is due to the different ways gases condensed into solids in the inner and outer regions of the solar nebula.

Even among the four Terrestrial planets, you will find a pattern of slight differences in density. The **uncompressed densities**—the densities the planets would have if their gravity did not compress them, or put another way, the densities of their original construction material—can be calculated from the actual densities and masses of each planet. In general, the closer a planet is to the Sun, the higher is its uncompressed density.

This density variation is understood to have originated when the solar system first formed solid grains. The kind of matter that condensed in a particular region would depend on the temperature of the gas there. In the inner regions, the temperature seems to have been 1500 K or so. The only materials that can form grains at this temperature are compounds with high melting points, such as metal oxides and pure metals, which are very dense, corresponding to the composition of Mercury. Farther out in the nebula it was cooler, and silicates (rocky material) could condense. These are less dense than metal oxides and metals, corresponding more to the compositions of Venus, Earth, and Mars. Somewhere farther from the Sun there was a boundary called the **ice line** beyond which water vapour could freeze to form ice. Not much farther out, compounds such as methane and ammonia could condense to form other ices. Water vapour, methane, and ammonia were abundant in the solar nebula, so beyond the ice line, the nebula was filled with a blizzard of ice particles, and those ices have low densities, as have the Jovian planets.

uncompressed density The density a planet would have if its gravity did not compress it.

ice line A boundary at a certain distance from the Sun beyond which the temperature is low enough for water vapour to freeze to form ice.

condensation sequence The sequence in which different materials condense from the solar nebula, depending on their distance from the Sun.

The sequence in which different materials condensed from the gas at different distances from the Sun is called the **condensation sequence** (Table 12.2). This is a hypothesis that says the planets that formed at different distances from the Sun would have accumulated from different kinds of materials. The original chemical composition of the solar nebula should have been

Table 12.2 The Condensation Sequence

Temperature (K)	Condensate	Object (Estimated Temperature of Formation, K)
1500	Metal oxides	Mercury (1400)
1300	Metallic iron and nickel	
1200	Silicates	
1000	Feldspars	Venus (900)
680	Troilite (FeS)	Earth (600)
		Mars (450)
175	H_2O ice	Jovian (175)
150	Ammonia–water ice	
120	Methane–water ice	
65	Argon–neon ice	Pluto (65)

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roughly the same throughout the nebula. The important factor was temperature. The inner nebula was hot, and only metals and rock could condense there; the outer nebula was cold, and so lots of ices as well as metals and rock could form. The ice line seems to have been between Mars and Jupiter, and it separates the formation of the dense Terrestrial planets from that of the lower-density Jovian planets.

Formation of Planetesimals

In the development of a planet, three groups of processes operate to collect solid bits of matter—rock, metal, or ices—into larger bodies called **planetesimals**, which eventually build the planets. The study of planet-building is the study of these three groups of processes: condensation, accretion, and gravitational collapse.

According to the solar nebula theory, planetary development in the solar nebula began with the growth of dust grains. These specks of matter, whatever their composition, grew from microscopic size first by condensation, then by accretion.

A particle grows by **condensation** when it adds matter one atom or molecule at a time from a surrounding gas. Snowflakes, for example, grow by condensation in Earth's atmosphere. In the solar nebula, dust grains were continuously bombarded by atoms of gas, some of which stuck to the grains.

planetesimal A small body that formed from the solar nebula and eventually grew into a protoplanet.

condensation The growth of a particle by addition of material from the surrounding gas, atom by atom.

accretion The sticking together of solid particles to produce a larger particle.

protoplanet Massive object, destined to become a planet, resulting from the coalescence of planetesimals in the solar nebula.

gravitational collapse The process by which a forming body such as a planet gravitationally captures gas rapidly from the surrounding nebula.

differentiation The separation of planetary material inside a planet according to density.

outgassing The release of gases from a planet's interior.

The second process is **accretion**, the sticking together of solid particles. You may have seen accretion in action if you walked through a snowstorm with big, fluffy flakes. If you caught one of those flakes on your mitten and looked closely, you could see that each of them was made up of many tiny, individual flakes that had collided as they fell and accreted to form larger particles. Model calculations indicate that in the solar nebula the dust grains were, on the average, no more than a few centimetres apart, so they collided frequently and accreted into larger particles.

There is no clear distinction between a very large grain and a very small planetesimal. An object can be considered a planetesimal when its diameter approaches a kilometre or so: the size of a typical small asteroid or comet.

Objects in the solar nebula larger than a centimetre were subject to processes that tended to concentrate them. For example, collisions with the surrounding gas and with each other would have caused growing planetesimals to settle into a thin disk, with an estimated thickness of about 0.01 AU in the central plane of the rotating nebula. This concentration of material would have made further planetary growth more rapid. Computer models show that the rotating disk of particles should have been gravitationally unstable and would have been disturbed by spiral density waves much like those found in spiral galaxies. This would have further concentrated the planetesimals and helped them coalesce into objects up to about 100 km in diameter.

Through these processes the nebula became filled with trillions of solid particles ranging in size from pebbles to small planets. As the largest began to exceed 100 km in diameter, new processes began to alter them, and a new stage in planet-building began: the formation of protoplanets.

Growth of Protoplanets

With the coalescing of planetesimals, **protoplanets** eventually formed—the massive objects destined to become planets. As these larger bodies grew, new processes began making them grow faster and altered their physical structure.

If planetesimals collided at orbital velocities, it is unlikely that they would have stuck together. The average orbital velocity in the solar system is about 10 km/s. Head-on collisions at this velocity would have vaporized the material. However, the planetesimals were all moving in the same direction in the nebular plane and didn't collide head-on. Instead, they merely "rubbed shoulders," so to speak, at low relative velocities. Such gentle collisions would have been more likely to combine them than to shatter them.

The largest planetesimals would grow the fastest because they had the strongest gravitational field and could more easily attract additional material. Computer models indicate that these planetesimals grew quickly to protoplanetary dimensions, sweeping up more and more material.

Protoplanets had to begin growing by accumulating solid material because they did not have enough gravity to capture and hold large amounts of gas. In the warm

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solar nebula, the atoms and molecules of gas were travelling at velocities much larger than the escape velocities of modest-size protoplanets. Because of that, in their early development, the protoplanets could grow only by attracting solid bits of rock, metal, and ice. Once a protoplanet approached a mass of 15 Earth masses or so, it could begin to grow by **gravitational collapse**, the rapid accumulation from the nebula of large amounts of infalling gas.

In its simplest form, the theory of Terrestrial protoplanet growth supposes that all the planetesimals in each orbital zone had about the same chemical composition. The planetesimals accumulated gradually to form a planet-size ball of material that was of homogeneous composition throughout. As the planet formed, heat accumulated in its interior both from the impacts of infalling planetesimals and from the decay of short-lived radioactive elements. This heat eventually melted the planet and allowed it to differentiate. **Differentiation** is the separation of material according to density. When the planet melted, the heavy metals such as iron and nickel settled to the core, while the lighter silicates floated to the surface to form a low-density crust. Figure 12.11 depicts the story of planet formation, including the accretion of planetesimals followed by differentiation.

This process depends on the presence of short-lived radioactive elements whose rapid decay would have released enough heat to melt the interior of planets. Astronomers know such radioactive elements were present because the oldest meteorites contain magnesium-26 that is produced by the radioactive decay of aluminum-26 with a half-life of only 0.74 million years. The aluminum-26 and similar short-lived radioactive elements are gone now, but they must have been produced in a supernova explosion that occurred no more than a few million years before the formation of the solar nebula. In fact, many astronomers suspect that this supernova explosion compressed nearby gas and triggered the formation of stars, one of which became the Sun. Our solar system may exist because of a supernova explosion that occurred about 4.6 billion years ago.

If planets formed and were later melted by radioactive decay, gases released from the planet's interior would have formed an atmosphere. The creation of a planetary atmosphere from a planet's interior is called **outgassing**. Models of the formation of Earth indicate that the local planetesimals would not have included much water, so some astronomers now think that Earth's water and some of its present atmosphere accumulated late in the formation of the planets, as Earth swept up volatile-rich planetesimals that were forming in the cooling solar nebula.

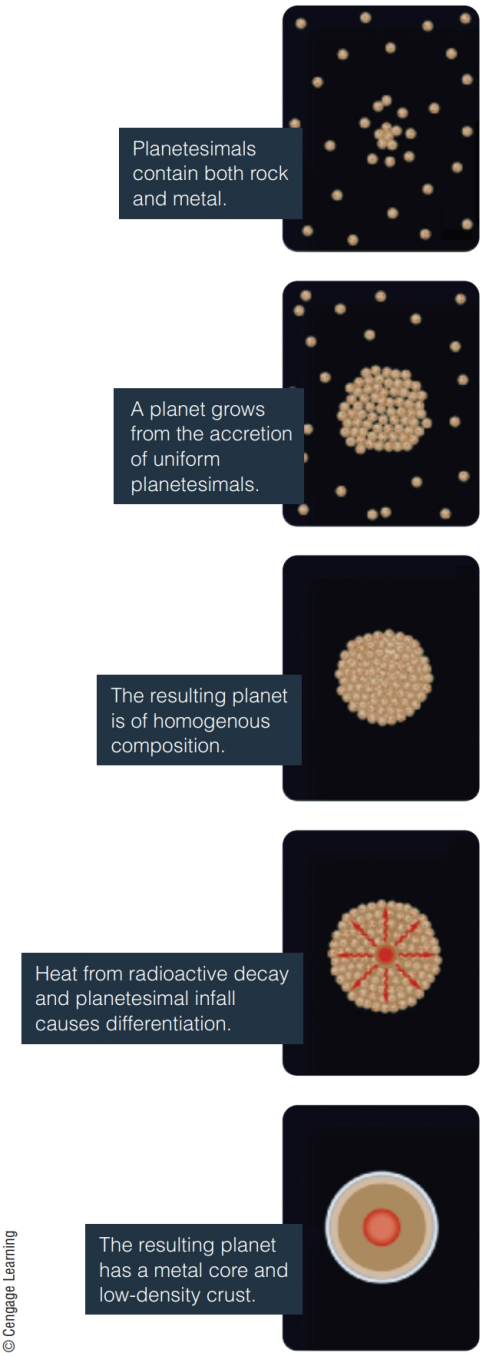


Figure 12.11 This simple model of accretion assumes planets formed from planetesimals that were of uniform composition, containing both metals and rocky material, and the planets later differentiated, meaning they melted and separated into layers by density and composition.

Such icy planetesimals may have formed in the outer parts of the solar nebula and been scattered by encounters with the Jovian planets, creating a solar system–wide bombardment of comets.

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heavy bombardment The intense cratering that occurred sometime during the first 0.5 billion years in the history of the solar system.

According to the solar nebula theory, the Jovian planets began growing by the same processes that built the Terrestrial planets, however the outer solar nebula contained not only solid bits of metals and silicates, but also abundant ices. The Jovian planets grew rapidly and quickly became massive enough to grow by gravitational collapse, drawing in large amounts of gas from the solar nebula. Ices could not condense as solids at the locations of the Terrestrial planets, so those planets developed slowly and never became massive enough to grow by gravitational collapse.

The Jovian planets must have grown to their present size in less than about 10 million years, which is when astronomers calculate that the Sun became hot and luminous enough for the solar wind to blow away the gas remaining in the solar nebula. The Terrestrial planets grew from solids, not from the gas, so they could have continued to grow by accretion from the solid debris left behind when the gas was blown away. Model calculations indicate the process of planet formation was almost completely finished by the time the solar system was about 30 million years old.

Bombardment of the Planets

Astronomers have good reason to believe that comets and asteroids can hit planets. Meteorites hit Earth every day, and occasionally a large one can form a crater (Figure 12.12). Earth is marked by about 150 known meteorite craters. In a sense, this bombardment represents the slow continuation of the accretion of the planets. Earth's moon, Mercury, Venus, Mars, and most of the moons in the solar system are covered with craters. A few of these craters have been formed recently by the steady rain of meteorites that falls on all planets in the solar system. However, most of the craters appear to have been formed more than 4 billion years ago in what is called the **heavy bombardment**; at that time much of the remaining solid debris in the solar nebula was swept up by the planets. In Chapter 13 you will learn that the heavy bombardment may have had more than one episode.

Sixty-five million years ago, at the end of the Cretaceous period, over 75 percent of the species on Earth, including the dinosaurs, went extinct. Scientists have found a thin layer of clay (called the K-Pg or K-T boundary) all over the world that was laid down at that time, and it is rich in the element iridium—common in meteorites but rare in Earth's crust. This suggests that a large impact altered Earth's climate and caused the worldwide extinction. Mathematical models predict that a major impact ejected huge amounts of pulverized rock high above the atmosphere. As this material fell back, Earth's atmosphere turned into a glowing oven of red-hot meteorites streaming through the air, and the heat triggered massive forest fires around the world. Soot from such fires has been found in the final Cretaceous clay layers. Once the firestorms cooled, the remaining dust in the atmosphere blocked sunlight and produced deep darkness for a year or more, killing off most plant life. Other effects, such as acid rain and enormous tsunamis (tidal waves), are also predicted by these models.


NEO/NASA

Figure 12.12 The Manicouagan crater in Quebec is one of the largest known impact craters on Earth, with a diameter of about 65 km. It is believed to have been created by an asteroid impact over 200 million years ago. The heat and pressure of the impact caused rings similar to the ripples of a stone dropped in water. An annular (ring-shaped) lake is visible in this photo taken from the space shuttle.

Planetary geologist Adriana Ocampo and her colleagues have located a crater at least 180 km in diameter centred near the village of Chicxulub (pronounced cheek-shoe-lube) in the northern Yucatán region of Mexico (Figure 12.13). Although the crater is completely covered by sediments, mineral samples show that it contains shocked quartz typical of impact sites and that it is the right age. The impact of an object 10 to 14 km in diameter formed the crater about 65 million years ago, just when the dinosaurs and many other species died out. Most Earth scientists now consider this to be the scar of the impact that ended the Cretaceous period.

Earthlings watched in awe during six days in the summer of 1994 as 20 or more fragments from the head of Comet Shoemaker–Levy 9 slammed into Jupiter and produced impacts equalling the detonation of

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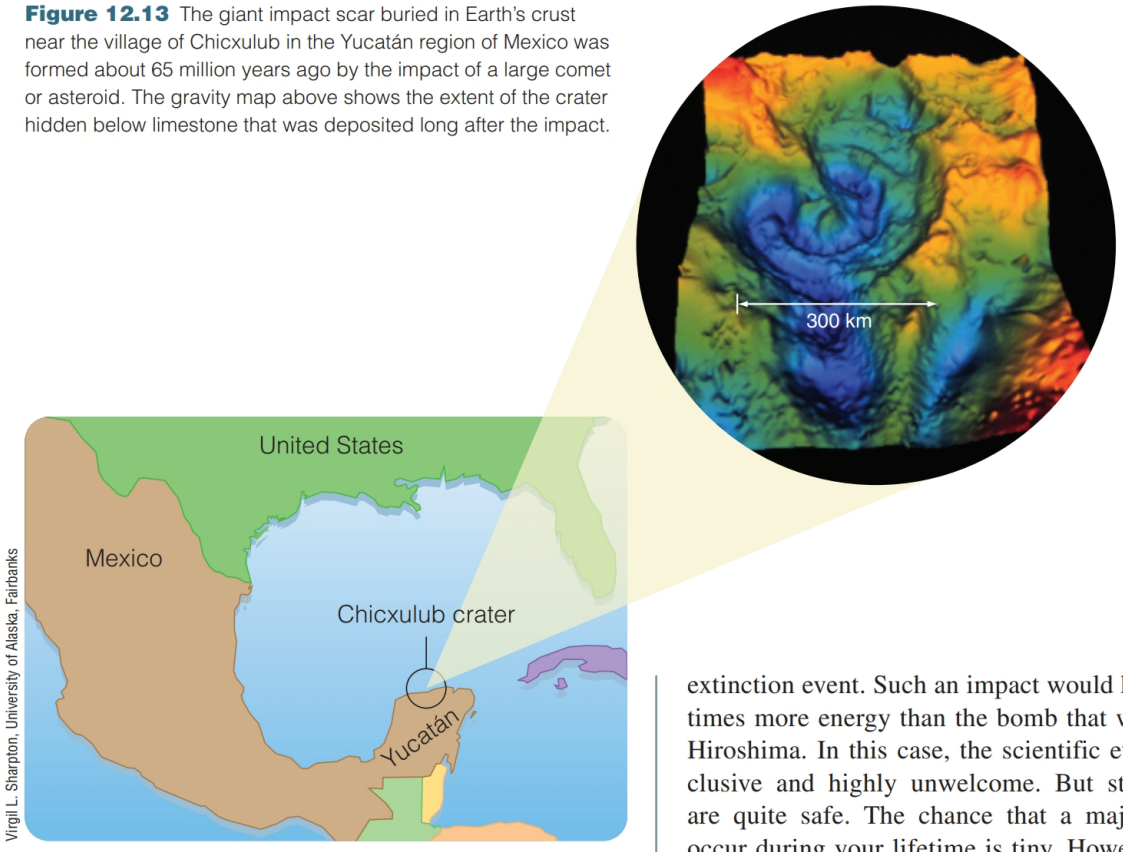


Figure 12.13 The giant impact scar buried in Earth's crust near the village of Chicxulub in the Yucatán region of Mexico was formed about 65 million years ago by the impact of a large comet or asteroid. The gravity map above shows the extent of the crater hidden below limestone that was deposited long after the impact.

millions of megatons of TNT. Each impact created a fireball of hot gases and left behind dark smudges that remained visible for months afterward (Figure 12.14). Another such impact produced a single scar observed in 2009. Carolyn and Eugene Shoemaker, David Levy, and Philippe Bendjoya were co-discoverers of Comet Shoemaker–Levy 9. American astronomer Carolyn Shoemaker holds the record for being the most successful comet hunter alive; remarkably, she accomplished this after she took up astronomy at age 51. Canadian amateur astronomer David Levy is the first person to have discovered comets using visual, photographic, and electronic methods.

Major impacts occur less often on Earth because Earth is smaller than the Jovian planets, but such impacts are inevitable. We are sitting ducks. All of humanity is spread out over Earth's surface and exposed to anything that falls out of the sky. Meteorites, asteroids, and comets bombard Earth, producing impacts that vary from dust settling on rooftops to blasts capable of destroying all life. As we know from the impact that led to the extinction of the dinosaurs, it would take an object of only a few kilometres in diameter to create a mass extinction event. Such an impact would have 10 million times more energy than the bomb that was dropped on Hiroshima. In this case, the scientific evidence is conclusive and highly unwelcome. But statistically, you are quite safe. The chance that a major impact will occur during your lifetime is tiny. However, the consequences of such an impact are so severe that humanity should be preparing. One way to prepare is to find the **NEOs (near-Earth objects)** that could hit this planet, map their orbits in detail, and identify any that are dangerous. Spaceguard programs around the world focus on surveying the skies to discover NEOs. These programs include Near-Earth Asteroid Tracking (NEAT); Catalina Sky Survey, the most prolific NEO discovery program; the Japan Spaceguard Association; Europe's Asiago DLR Asteroid Survey; and the Beijing Schmidt CCD Asteroid Program. You can help too, by joining the growing global network of amateur astronomers who are watching the skies from their backyards and helping to guard our planet.

Explaining the Characteristics of the Solar System

Now you have learned enough to put all the pieces of the puzzle together and explain the distinguishing characteristics of the solar system as outlined in Table 12.1.

NEO (near-Earth object) A small solar system body (asteroid or comet) with an orbit near enough to Earth that it poses some threat of eventual collision.

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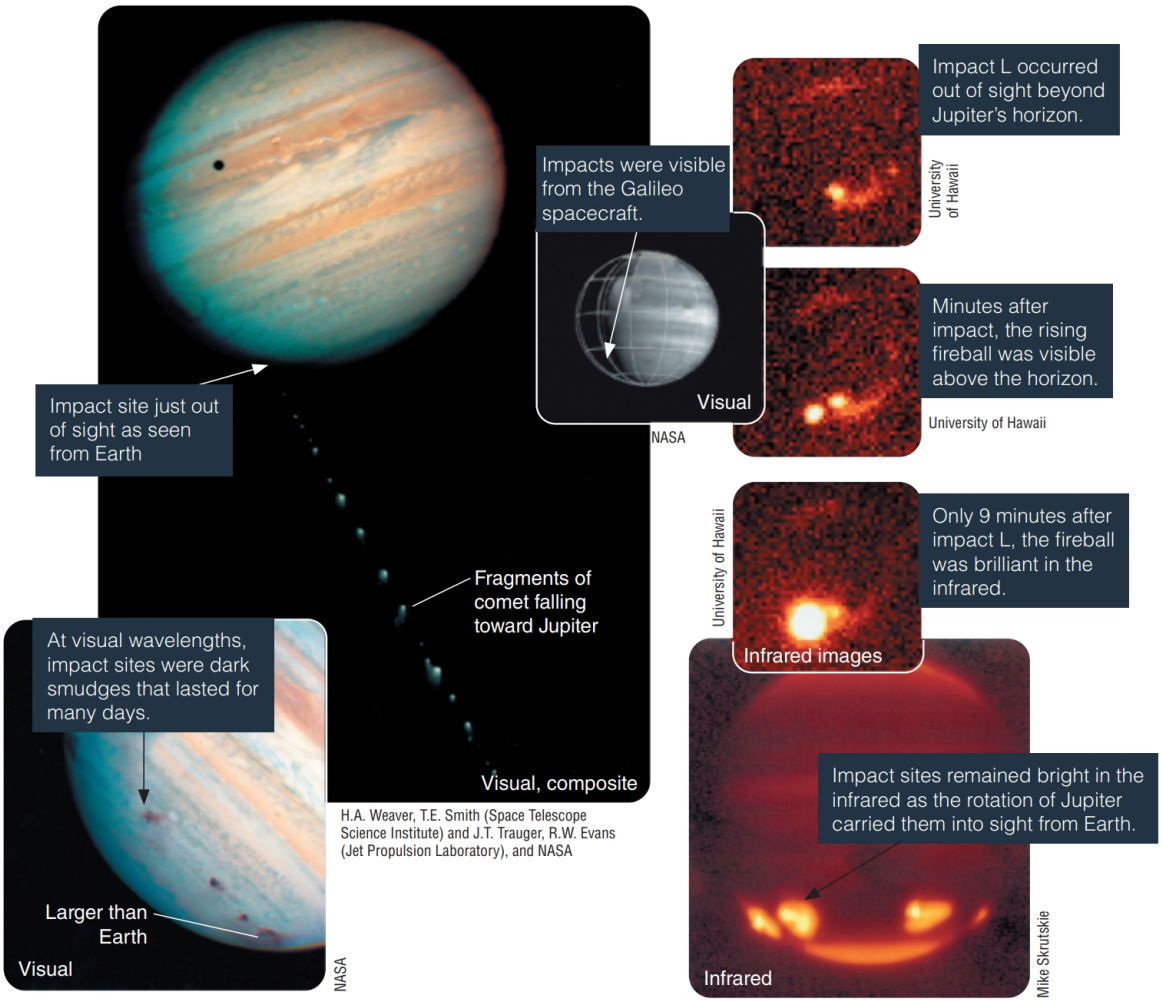


Figure 12.14 The impact of Comet Shoemaker–Levy 9 with Jupiter was the first collision between two objects in our solar system that was directly observed from Earth.

The first fact in Table 12.1 is that the Sun and planets revolve and rotate in the same direction. This happens because they formed from the same rotating gas cloud. Also, the orbits of the planets lie in the same plane because the rotating solar nebula collapsed into a disk, and the planets formed in that disk.

evolutionary theory An explanation of a phenomenon involving slow, steady processes.

catastrophic theory An explanation of a phenomenon involving special, sudden, perhaps violent, events.

According to the solar nebula theory, continuing evolutionary processes gradually build the planets. Scientists call this type of explanation an **evolutionary theory**. In contrast, a **catastrophic theory** invokes special, sudden, even violent, events. For example, the peculiarities of rotation of Uranus, which rotates on its side, and Venus, which rotates backward, could have been caused by an off-centre impact of a massive planetesimal on each planet while they were forming—an explanation of the catastrophic type. Similarly, Earth's unusually large moon could be a result of a giant impact that stripped debris from Earth, which accreted to form the Moon. On the other hand, computer models suggest that the Sun can produce tides in the thick atmosphere of Venus, which eventually could have resulted in the reversal of that planet's rotation—an explanation of the evolutionary type.

The second point in Table 12.1 refers to the division of the planets into Terrestrial and Jovian worlds, which can be explained by the condensation sequence. The Terrestrial planets formed in the inner part of the solar

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nebula, where the temperature was high, and only compounds such as metals and silicates could condense to form solid particles. That produced the small, dense Terrestrial planets. In contrast, the Jovian planets formed in the outer solar nebula, where the lower temperature allowed the gas to form large amounts of ices, perhaps three times more ices than silicates. That allowed the Jovian planets to grow rapidly and become massive, low-density worlds. Also, the massive planets Jupiter and Saturn eventually grew even larger by drawing in gas directly from the solar nebula. The Terrestrial planets could not do this because they never became massive enough.

The **heat of formation** (the energy released by infalling matter) was tremendous for these massive planets. Jupiter must have grown hot enough to glow with a luminosity of about 1 percent that of the present Sun. However, because it never got hot enough to start nuclear fusion as a star would, it never generated its own energy. Jupiter is still hot inside. In fact, both Jupiter and Saturn radiate more heat than they absorb from the Sun, so they are evidently still cooling.

Mathematical models show Jupiter grew into such a massive planet that it was able to gravitationally disturb the motion of nearby planetesimals. The bodies that might have formed a planet between Mars and Jupiter were broken up, thrown into the Sun, or ejected from the solar system due to the gravitational influence of massive Jupiter. The asteroids seen today are the last remains of those rocky planetesimals.

The comets, in contrast, are evidently the last of the icy planetesimals. Some may have formed in the outer solar nebula beyond Neptune, but many probably formed among the Jovian planets, where ices could condense easily. Mathematical models show that the massive Jovian planets could have ejected some of these icy planetesimals into the far outer solar system, into the region of the Oort cloud, from which come comets that have very long periods and orbits that are highly inclined to the plane of the solar system.

The icy Kuiper belt objects, including Pluto, appear to be ancient planetesimals that formed in the outer solar system but were never incorporated into a planet. They orbit slowly far from the light and warmth of the Sun and, except for occasional collisions, have not changed much since the solar system was young. You will learn more about Pluto's origins and differences from the other outer planets in Chapter 14.

The third point in Table 12.1 notes that all four Jovian worlds have ring systems and numerous moons. To understand this, consider the large mass of these worlds and their remote location in the solar system. A large mass makes it easier for a planet to hold on to orbiting ring particles, and, being farther from the Sun, the ring particles are not as easily swept away by the pressure of sunlight and the solar wind. So it is not surprising that the Terrestrial planets, low-mass worlds located near the Sun, have no planetary rings. As the Jovian planets formed, spinning, flattening, and heating formed disks of material around them. Condensation and accretion occurred in these mini solar systems, leading to the formation of numerous large moons. For example, Jupiter has over a dozen moons. In contrast, Earth is the only Terrestrial planet to have an unusually large moon. You will learn more about Earth's moon and the Jovian moons in Chapters 13 and 14.

The fourth point in Table 12.1 refers to the common ages of solar system bodies. The solar nebula theory has no difficulty explaining that characteristic because it predicts that the planets formed at the same time as the Sun, and they should all have roughly the same age.

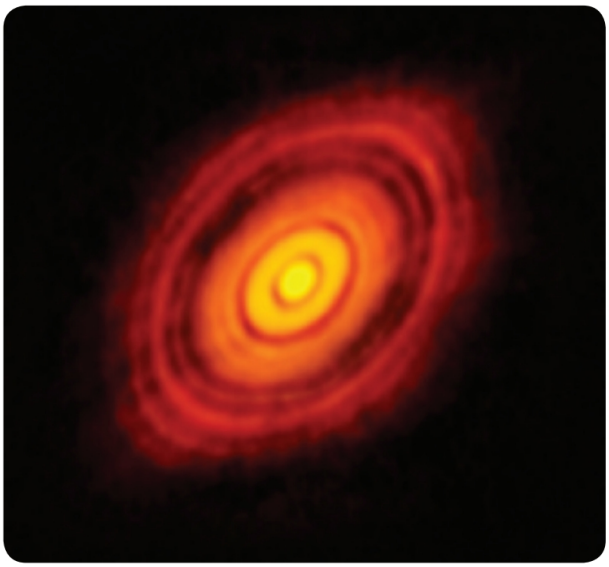
12.5 Planet-Forming Disks Around Young Stars

The nebular theory of planet formation does a good job of accounting for the characteristics of our solar system. We learned in Chapter 7 that dense disks of gas and dust surround stars that are still in the process of forming. The disks of gas and dust that surround most of the stars in the Orion Nebula have more than enough mass to make planetary systems like our own. How can we tell whether these disks are actually forming planets?

Recent advances in astronomical technology have made it possible to image the cold dust and gas surrounding very young stars. Figure 12.15 shows an image of a protoplanetary disk around the star HL Tau, taken with the Atacama Large Millimeter/submillimeter Array (ALMA). HL Tau is a Sun-like star less than a million years old whose disk shows prominent ring-like structures, reminiscent of the rings of Saturn. And as with the rings of Saturn, the gaps in the disk of HL Tau are believed to be caused by the gravity of compact, dense objects. These dense objects in the disk around HL Tau are planetesimals and forming planets.

heat of formation In planetology, the heat released by infalling matter during the formation of a planetary body.

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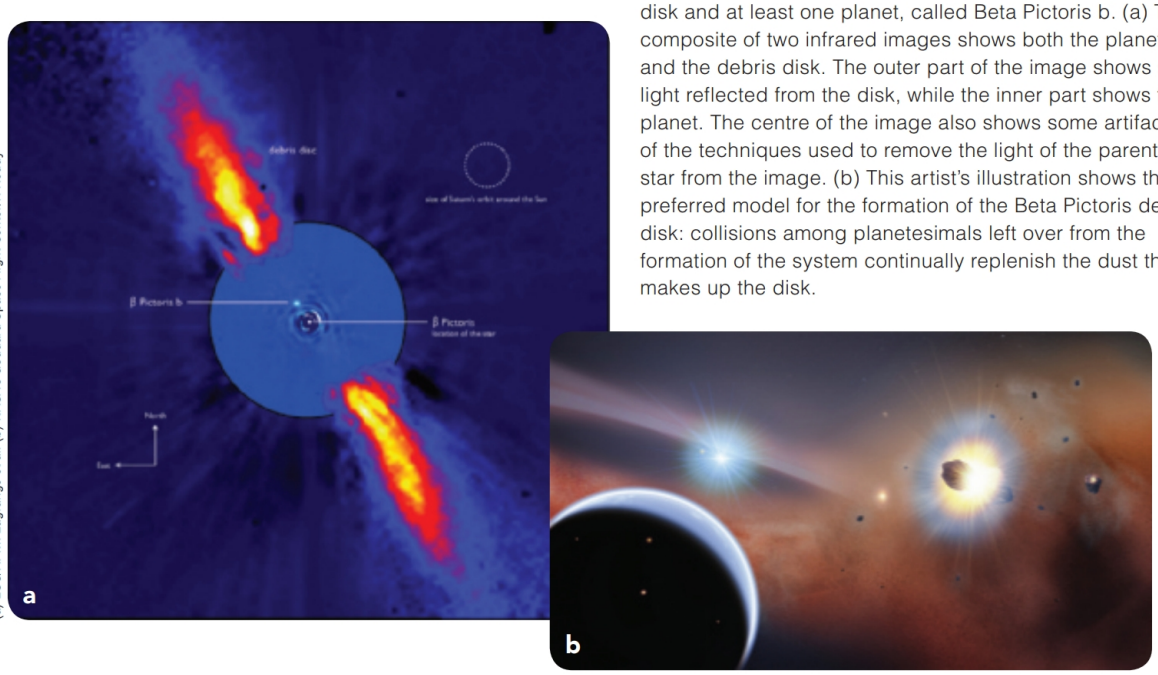
ALMA (ESO/NAOJ/NRAO)/NASA/ESA, CC BY-SA 3.0 IGO

Figure 12.15 This image of a protoplanetary disk around the star HL Tau shows rings and gaps caused by the gravity of forming planets. The image, which mainly shows cool dust, was taken using light of submillimetre wavelengths, in the far infrared portion of the spectrum. The star itself is buried deep in the centre of the disk. Contrast this image with the middle panel of Figure 12.1.

debris disk A disk of dust around some stars, found by infrared observations. The dust is debris from collisions among asteroids, comets, and Kuiper belt objects.

In addition to these planet-forming disks around young stars, infrared astronomers have found cold, low-density dust disks around older stars such as Vega and Beta Pictoris. Although much younger than the Sun, these stars are on the main sequence and have completed their formation, so they are clearly in a later stage than the newborn stars in Orion. These low-density disks generally have even lower-density inner zones where planets may have formed (see Figure 12.16). Such tenuous dust disks are sometimes called **debris disks** because they are understood to consist of dusty debris released during collisions among small bodies such as comets, asteroids, and Kuiper belt objects. Our own solar system contains such dust, and astronomers have evidence that the Sun has an extensive debris disk of cold dust extending far beyond the orbits of the planets. Many of the debris disks have details of structure and shape that are probably caused by the gravity of planets orbiting within or at the edges of the debris.

Notice the difference between the two kinds of disks that astronomers have found: debris disks and protoplanetary disks. The low-density dust disks such as the one around Beta Pictoris are produced by dust from collisions among remnant planetesimals, such as comets, asteroids, and Kuiper belt objects. Such disks are evidence that planetary systems have already formed. In contrast, the dense disks of gas and dust, such as the one seen in Figure 12.16, are sites where planets could be forming right now.



(a) ESO/A.-M. Lagrange et al. (b) NASA's Goddard Space Flight Center/F. Reddy

Figure 12.16 The star Beta Pictoris hosts both a debris disk and at least one planet, called Beta Pictoris b. (a) This composite of two infrared images shows both the planet and the debris disk. The outer part of the image shows starlight reflected from the disk, while the inner part shows the planet. The centre of the image also shows some artifacts of the techniques used to remove the light of the parent star from the image. (b) This artist's illustration shows the preferred model for the formation of the Beta Pictoris debris disk: collisions among planetesimals left over from the formation of the system continually replenish the dust that makes up the disk.

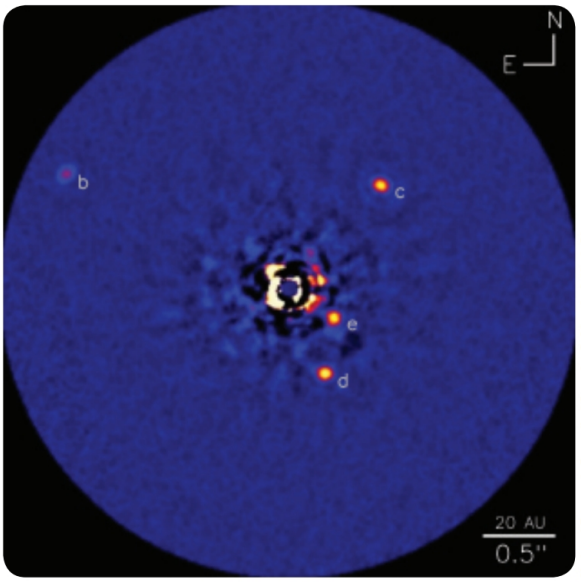
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12.6 Exoplanets: Planets Orbiting Other Stars

For thousands of years, scientists and philosophers have wondered whether every star in the sky was orbited by planets. And, if so, were any of those planets Earth-like? We are now ready to explore this question.

A planet orbiting another star is called an extrasolar planet or **exoplanet**. You might imagine that taking pictures of planets orbiting nearby stars should be no trouble at all, given that astronomers routinely take pictures of galaxies billions of light years away. Actually, photographing exoplanets—a technique called direct imaging—is extremely challenging with current technologies. It's a bit like trying to take a picture of a firefly buzzing near a stadium light: the stadium light overwhelms the camera and makes it impossible to see the firefly. In the same way, exoplanets are usually lost in the glare of the stars they orbit. Observing at infrared wavelengths, where the star is dimmer and the planet brighter, makes it slightly easier to image exoplanets. Adaptive optics (see Chapter 4) and digital post-processing can further improve the image. These methods make it possible to photograph young Jupiter-sized planets orbiting far from their parent stars. Since 2008, an international team led by Christian Marois of the Herzberg Astronomy and Astrophysics Research Centre in Victoria have been using the Gemini and Keck telescopes to image four exoplanets orbiting the star HR 8799 (see Figure 12.17). With several years of observations, they are able to actually watch the planets orbit the star. Spectra

exoplanet A planet orbiting a star other than the Sun.



National Research Council of Canada, C. Marois & Keck Observatory

Figure 12.17 This image shows four exoplanets, labelled b, c, d, and e, orbiting the star HR 8799. A combination of telescope optics and digital post-processing have removed most of the starlight from the image, but some still remains toward the centre. Each planet is only visible as an unresolved speck.

CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Photo Courtesy of René Doyon

René Doyon

René Doyon

René Doyon searches for new worlds. As a professor at the University of Montreal, he has made his career building new instruments to advance the search for Earth-like exoplanets. In 2008, he was part of a team of astronomers who produced the first-ever photograph of a multi-planet solar system. This image, a version of which is shown in Figure 12.17, was the realization of the dreams of generations of stargazers. The team was led by his former student Christian Marois and included another former student, David Lafrenière. Doyon's research group has produced many of the world's leading experts in the field of direct imaging of exoplanets.

Doyon is on the forefront of international efforts to not only image exoplanets, but also characterize their atmospheres. He is co-principal investigator of SPIRou, an instrument being built for the Canada-France-Hawaii Telescope. SPIRou will search for potentially habitable Earth-sized exoplanets using the Doppler method. Its observations will complement those of NASA's TESS telescope, which is searching for exoplanets around nearby bright stars. Doyon also led the development of two instruments for the upcoming James Webb Space Telescope, including a spectrograph that, it is hoped, will be able to measure the chemical composition of the atmospheres of Earth-like exoplanets—and perhaps even detect the presence of gases indicative of life.

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of these exoplanets show that their atmospheres contain many of the same chemicals as the gas giants of our own solar system, including methane, carbon monoxide, and water.

Most exoplanets that can be directly imaged today are Jupiter-mass planets orbiting far from their parent stars. They are detectable mainly because they are still releasing the heat left over from their formation. Direct imaging of smaller, cooler Earth-like planets is not yet possible. Instead, astronomers have devised many *indirect* detection methods, capable of identifying planets even smaller than Earth, orbiting close to their parent stars. These indirect methods don't generate a photo of the exoplanets, but a surprising amount can be learned about them even so.

The simplest indirect method for finding exoplanets is the **transit method**. When an exoplanet passes in front of its parent star, it blocks some of the light from the star, as shown in Figure 12.18. The dimming of the star is very small, but it is detectable. If the dimming repeats many times at regular intervals, we can be confident that it is caused by an object orbiting the star. By measuring the amount of dimming, the size of the object can be calculated and astronomers can work out whether it is a planet or perhaps a binary stellar companion.

transit method A technique for finding exoplanets by searching for the dimming of their parent stars when the planet passes in front of the star.

The transit method has been the most successful method for finding exoplanets to date, with approximately 3000 confirmed exoplanets discovered using this method, and likely thousands more to come in the next few years. Most of these planets were identified by NASA's *Kepler* space telescope, which operated from 2009 until 2018. *Kepler* focused on a single patch of sky near the constellation Cygnus, staring at it with few interruptions for years. *Kepler* has identified a stunning variety of different types of planets, including many that are not found in our own solar system. These include "super-Earth" planets, with masses intermediate between those of Earth and Neptune. Some of these may be ocean worlds—planets with thick oceans of water or other fluids that may be of interest in the search for life beyond our solar system.

Despite its many successes, the transit method has important limitations. It relies on a chance alignment of the planet's orbital plane with our line of sight, a configuration astronomers call "edge-on." Planetary systems orbit their stars at random angles to our line of sight, so only a few percent are close enough to edge-on for the transit method to detect them. Also, the transit method can tell us the *sizes* of exoplanets, but not their *masses*. Astronomers need both pieces of

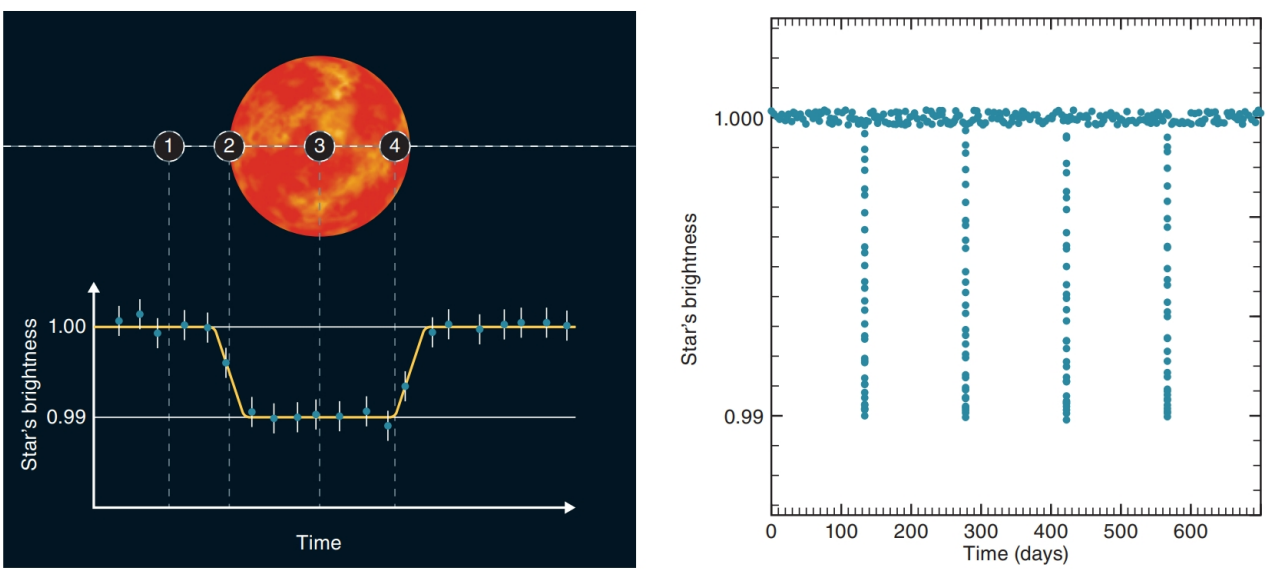


Figure 12.18 (a) In the transit method for detecting exoplanets, the existence of an unseen planet is inferred from measurements of the brightness of its parent star, called a light curve. The star is seen as a single point of light whose brightness drops when the planet passes in front of the star (from our perspective). The amount of dimming is related to the size of the planet, with larger planets blocking more light and producing larger dips in the light curve. (b) If the dimming occurs many times at regular intervals, we can be confident it is caused by an object orbiting the star.

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information to calculate the densities of these planets, which indicate whether a planet is a rocky terrestrial planet, a partially gaseous planet like Saturn, or something in between.

Another indirect detection method, called the **Doppler method** or the radial velocity method, relies on detecting the motion of a star in response to the gravity of one or more unseen planets in orbit around it. Recall that two stars in a binary system orbit their shared centre of mass. When a planet orbits a star, the star moves very slightly as it orbits the centre of mass of the planet–star system. Think of someone walking a poorly trained dog on a leash; the dog runs around pulling on the leash, and even if it were an invisible dog, you could plot its path by watching how its owner was jerked back and forth. Astronomers can detect a planet orbiting another star by watching how the star moves as the planet tugs on it. The motion of the star is revealed by the Doppler shift of the star's spectrum (see Chapter 5), as shown in Figure 12.19. This technique is the same as the one used to study spectroscopic binary stars (see Chapter 6, Figure 6.13), except that the Doppler shifts produced by orbiting planets tend to be much smaller and therefore much more difficult to detect.

In 1988, Canadian astronomers Bruce Campbell, G. A. H. Walker, and S. Yang discovered the first extrasolar planet using this method, but their discovery was not confirmed until 2002. This planet orbits in the Gamma Cephei system, a binary star system consisting of a red dwarf star and a K-class giant. The first planet orbiting an isolated sunlike

Doppler method A technique for finding exoplanets by searching for periodic Doppler shifts in the spectra of stars. The shifts are caused by the star and an unseen planet orbiting their common centre of mass.

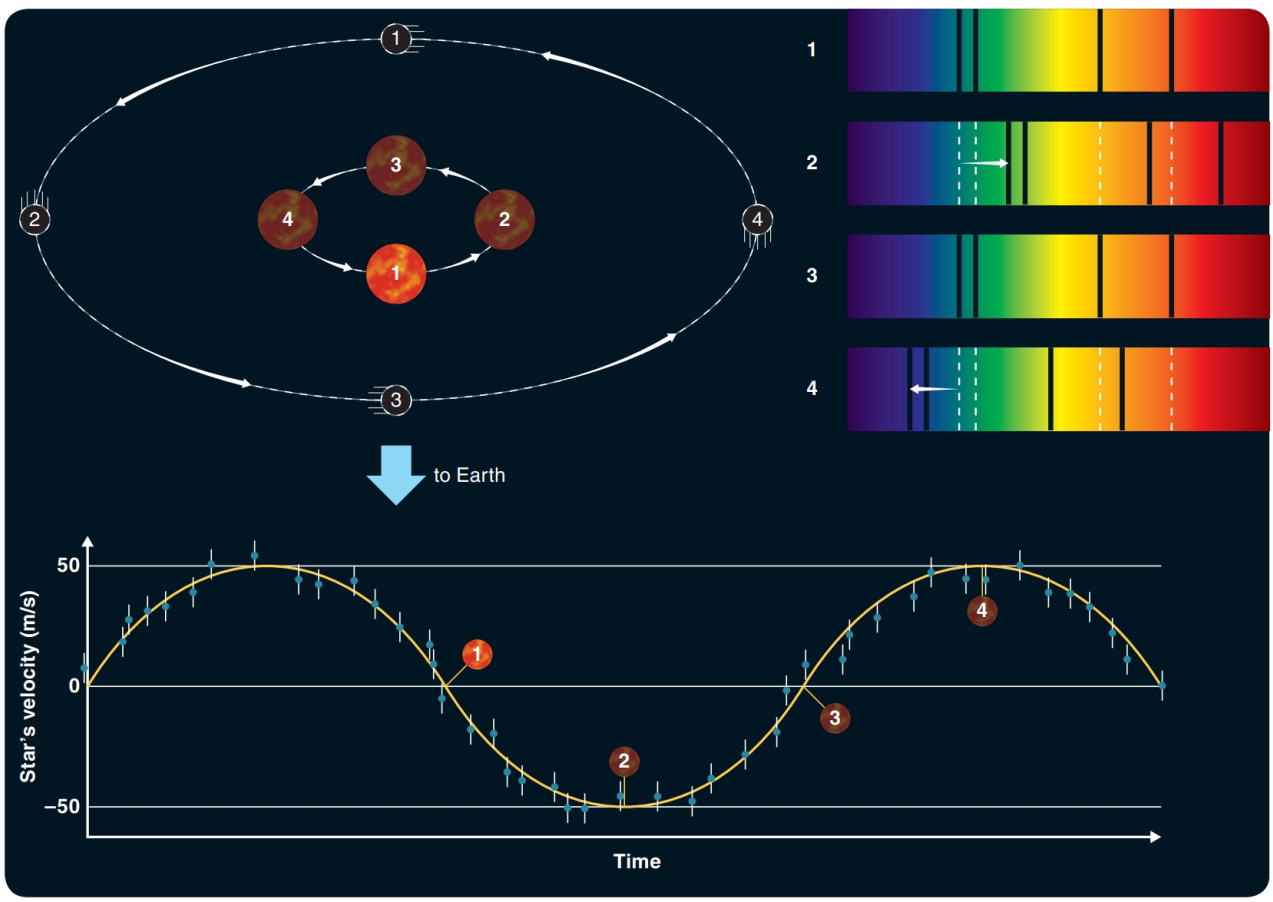


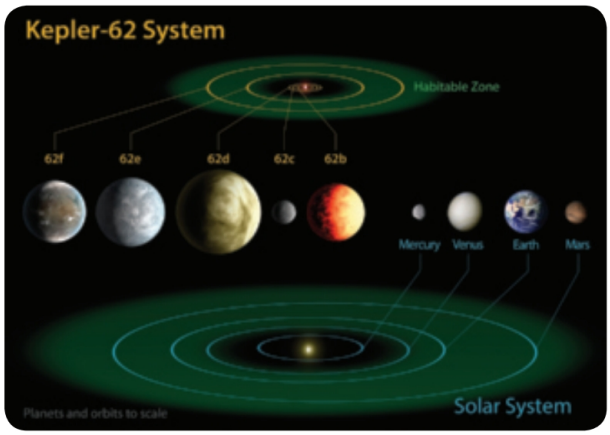
Figure 12.19 In the Doppler method, the presence of an unseen planet is revealed by the motion it induces in its parent star. As the planet and the star orbit their common centre of mass, absorption lines in the star's spectrum undergo a Doppler shift. When the star and planet are moving perpendicular to our line of sight, we obtain the spectrum of the star as if it were at rest (times 1 and 3). When the star is moving away from us, its spectrum is redshifted (time 2). Similarly, when the star is moving toward us, it spectrum is blueshifted (time 4). The motion of the planet is opposite to that of the star, as they orbit one another.

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star was discovered in 1995 by Swiss astrophysicist Michel Mayor and his Ph.D. student Didier Queloz. This planet, which orbits the star 51 Pegasi (and is therefore called 51 Pegasi b), was a big surprise to astronomers. It was the first discovery of a class of planets that does not exist in our own solar system: the so-called "hot Jupiters." It has a mass approximately half that of Jupiter, but its orbital period is only four days, meaning that it orbits its star at a distance of only 0.05 AU—significantly closer than Mercury is to the Sun. Hot Jupiters are much easier to detect using the Doppler method than smaller planets, or those orbiting farther from their stars. Can you work out why? Smaller planets orbiting farther from their parent stars produce smaller forces of gravity on those stars, in accordance with Newton's law of gravity. This means the Doppler shift they induce in the spectra of their parent stars is much smaller and harder to detect. So, in retrospect, it's no surprise that many of the planets first detected using the Doppler method were hot Jupiters.

One of the goals of the search for exoplanets is finding Earth-like planets in other solar systems. Using the transit and Doppler methods, plus a handful of others, astronomers have identified more than 4000 exoplanets, of which around 300 are similar in size to Earth. Of these, a few dozen orbit within the habitable zones of their parent stars. The habitable zone is the range of distances from a star within which water could remain liquid on a planetary surface for long periods of time (see Chapter 15). Determining whether or not a planet is actually habitable is a complex process. Extraterrestrials observing our own solar system with a similar level of technology to our own could certainly detect the existence of Venus, Earth, and Mars. But knowing only their size, mass, and distance from the Sun, would they conclude that they were habitable? Without knowing about Venus's crushingly thick atmosphere or Mars's extremely tenuous one, any conclusions they drew about habitability would be provisional at best. For most exoplanets, measuring the composition and density of their atmospheres is beyond our current technology. So, claims of having found "another Earth" are premature. However, there are some planets that give us cause for hope.

In 2013, astronomers using the Kepler space telescope announced the discovery of the Kepler-62 system. This system contains five known planets (see Figure 12.20), with radii ranging from half to twice that of Earth. Two of them, Kepler-62e and f, lie within the habitable zone of the star, which is a main-sequence K star, somewhat similar to the Sun. These two planets have masses of 4.5 and 2.8 Earth masses,

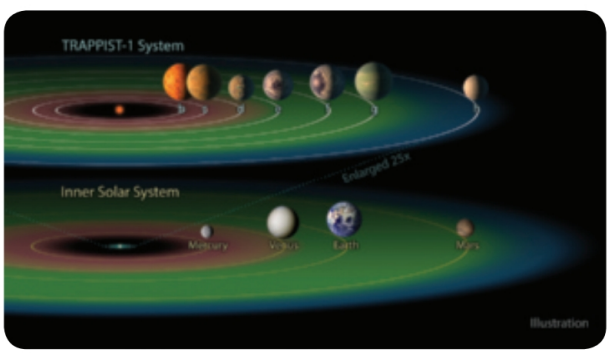


NASA Ames/JPL-Caltech

Figure 12.20 At least five planets orbit the star Kepler-62. Of these, two orbit within its habitable zone: Kepler-62e and f. The star is of class K, so it's cooler than the Sun and its habitable zone is therefore closer to the star. The system lies approximately 1200 light-years from Earth. The inner four planets of our own solar system are shown to scale, for comparison.

making them super-Earth planets. Depending on their atmospheric composition and density, they may be genuinely Earth-like.

Much closer to home than Kepler-62 is the TRAPPIST-1 system, a mere 40 light-years from Earth, shown in Figure 12.21. There are seven planets known to be orbiting TRAPPIST-1, all within 25 percent of the size of Earth. At least three of them are within the habitable zone. Precision measurements of the densities of these planets show that they are at least as varied as the terrestrial planets of our own solar system. Some appear to be nearly bare rock, while others have a thick layer of what may be water or ice. But don't make your extraterrestrial vacation plans just yet: the TRAPPIST-1 planets are very different from those in our solar system in some



NASA/JPL-Caltech

Figure 12.21 The planets of the TRAPPIST-1 system orbit very close to their parent star, a red dwarf. All of them are similar in size to Earth and at least three orbit in the habitable zone, shown here in green. The inner planets of our own solar system are shown for scale.

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important ways. TRAPPIST-1 is a very low-mass, cool red dwarf star, so its habitable zone is tucked in very close to the star. Their proximity to the star means that these potentially habitable planets are probably all tidally locked to it, just as the Moon is to Earth (see Chapter 3). With one side of each planet permanently facing the star, conditions on these planets would be very different from those on Earth. On one side, there would be perpetual daylight; on the other, perpetual night. Yet, because they are so close to Earth, astronomers will continue to study them in detail to try to determine whether any of them might be the sought-after "Earth 2.0."

Exoplanet searches have turned up many highly unusual and often fanciful systems. Kepler-16b is a circumbinary planet, orbiting a pair of stars instead of just one. The nearest exoplanet to our solar system, Proxima Centauri b, only 4.2 light-years away, orbits one member of a triple-star system. KELT-9b is a hot Jupiter that whirls around a hot B star in a 1.5-day orbit. Its searing temperature of more than 4000 K means that its outer layers are being slowly stripped away. Kepler-1625b is a Jupiter-size exoplanet which may have a Neptune-size moon. The diversity of exoplanets found in the last few decades is providing crucial evidence about how solar



HOW DO WE KNOW? 12.1

Scientists: Nature's Detectives



Microgen/Shutterstock.com

"Scientists are just a bunch of skeptics who don't believe in anything." That is a common misconception among people who don't understand the methods and goals of science. Scientists are skeptical not because they want to disprove everything but because they want to be sure that a new description of nature is correct before it is accepted.

Skeptical scientists question every aspect of a new discovery. They may wonder if another scientist's instruments were properly calibrated or if the scientist's mathematical models are correct. Other scientists will want to repeat the work themselves using their own instruments to see if they can obtain the same results. Observations are tested, discoveries are confirmed, and only an idea that survives many of these tests begins to be accepted as a scientific idea.

Scientists are prepared for this kind of treatment at the hands of other scientists. In fact, they expect it. Among scientists it is not bad manners to say, "Really, how do you know that?" or "Why do you think that?" or "Show me the evidence!" And it is not just new or surprising claims that are subject to such scrutiny. Astronomers had long expected to discover planets orbiting other stars. But when a planet was finally discovered circling 51 Pegasi, astronomers were skeptical—not because they thought the observations were flawed but because that is how science works.

Some people use the phrase "telling a story" to describe someone who is telling a fib. But the stories that scientists tell are exactly the opposite; perhaps you could call them antifibs, because they are as true as scientists can make them. Skepticism eliminates stories with logical errors, flawed observations, or misunderstood evidence and eventually leaves only the stories that best describe nature.

Just as a good detective must examine all the evidence, question everyone, and develop a theory that best fits the facts of the case, a good scientist also must "question everything," examine all the scientific evidence, and develop a scientific theory that best fits all the data. Even a single violation of a scientific theory is sufficient to invalidate the theory. Imagine what would happen if a single apple were to defy the theory of gravity and begin to float! Scientists could not ignore such an event. The exception does not prove the rule. Such new observations would lead to further studies and theories that took these new results into account. Hence, science progresses through conscientious skepticism.

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systems form and about the possible abundance of habitable planets in the cosmos.

One startling outcome of exoplanet searches is that astronomers now estimate there could be several billion Earth-sized planets in the Milky Way Galaxy. We are getting closer to answering the question: "Are we alone?"

The **Big Picture**

The matter you are made of came from the big bang, and it has been cooked into a wide range of atoms inside stars. Now you can see how those atoms came to be part of Earth. Your atoms were in the cloud of gas that formed the Sun 4.6 billion years ago, and nearly all of that matter contracted to form the Sun, but a small amount left behind in a disk formed planets. In the process, your atoms became part of Earth.

Are there other planet-walkers like you in the universe? Now you know that planets are common, and you can reasonably suppose that there are more planets in the universe than there are stars, suggesting there may indeed be planet-walkers living on other worlds.

Review and **Discussion Questions**

Review Questions

1. What produced the helium now present in the Sun's atmosphere? In Jupiter's atmosphere? In the Sun's core?
2. What are the observed properties of the solar system that must be explained by the theory of its origin?
3. What is the evidence that the solar system formed about 4.6 billion years ago?
4. According to the solar nebula theory, why is Earth's orbit nearly in the plane of the Sun's equator?
5. Why does the solar nebula theory predict that planetary systems are common?
6. How do planets form?
7. What is the difference between condensation and accretion?
8. What does the term *differentiated* mean when applied to a planet? Would you expect to find that planets are usually differentiated? Why?
9. What are asteroids and comets, what are their connections to meteors and meteorites, and what clues do they give about the origin of the solar system?
10. What processes cleared the nebula away and ended planet forming?
11. Why is almost every solid surface in our solar system scarred by craters?
12. Why would the formation of Jovian planets be difficult to understand if gas and dust disks around forming stars had short lifetimes in astronomical terms?
13. How does the solar nebula theory explain the dramatic density difference between the Terrestrial and Jovian planets?
14. By what methods have the extrasolar planets been discovered?
15. In what sense are the transit and Doppler methods for finding exoplanets "indirect"?
16. What information about exoplanets is typically lacking to make a full assessment of whether they are "Earth-like"?

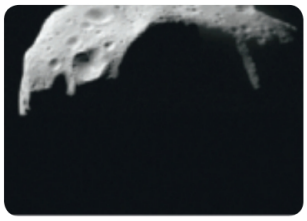
Discussion Questions

1. If you visited some other planetary system while the planets were forming, would you expect to see the condensation sequence at work, or was that most likely unique to our solar system? How do the properties of the extrasolar planets discovered so far affect your answer?
2. In your opinion, do most planetary systems have asteroid belts? Would all planetary systems show evidence of an age of heavy bombardment?
3. Do you think the government should spend money to find NEOs (near-Earth objects)? How serious is the risk?

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Learning to Look

1. What do you see in this image of the nucleus of Comet Borrelly that tells you how comets produce their tails?



NASA

2. What do you see in the image below that indicates this planet formed far from the Sun?



NASA/JPL/Space Science Institute

3. Why do astronomers conclude that the surface of Mercury, shown below, is old? When did the majority of those craters form?



NASA

STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *Life on Other Worlds.*

ONLINE

- Visit MINDTAP for ASTRO3 at nelson.com/student
- eBook
- Interactive Quizzing
- Animations
- Tutorials

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PART FOUR

13 Comparative Planetology of the Terrestrial Planets


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CHAPTER OUTLINE

13.1 A Travel Guide to the Terrestrial Planets
13.2 Earth: The Active Planet
13.3 The Moon
13.4 Mercury
13.5 Venus
13.6 Mars

GUIDEPOST

In 1600, the monk Giordano Bruno was burned at the stake in Rome. One of his many offences was teaching that Earth was a planet that rotates on its axis and revolves around the Sun. You know that Earth is a planet, but what is a planet? In this chapter and the next, you will study the planets of our solar system and you will learn what defines a planet. In this chapter you start with the planets that, like Earth, are made of rock and metal, and you will find answers to four important questions:

- Why are some planets cratered, airless worlds while others have atmospheres and weather?
- How does size and distance from the Sun influence the evolution of planets?
- How does the history of the Moon illuminate the history of Earth and the other planets?
- How does evidence tell planetary scientists that Venus and Mars were once more Earth-like?

comparative planetology Understanding planets by searching for and analyzing contrasts and similarities among them.

You can learn about the unearthly worlds of our solar system by using **comparative planetology**, the study of planets by comparison and contrast. As you study these planets, you will learn more about our own world. Understanding

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Once you've been in space, you appreciate how small and fragile the Earth is.

Valentina Tereshkova, cosmonaut, first woman in space

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the terrible heat of Venus and the frigid deserts of Mars will tell you more about our own beautiful planet. In the next chapter, you will meet even stranger worlds in the outer solar system, but they too will help you see Earth in new light.

13.1 A Travel Guide to the Terrestrial Planets

In this chapter you will visit five worlds: Earth, Earth's moon, Mercury, Venus, and Mars. This preliminary section is your guide to important features and comparisons.

The Scale of the Solar System

You can begin with the most general view of the solar system, which is almost entirely empty space (refer to **Visualizing Astronomy 1.1, The Scale of the Very Small and Very Large: Powers of 10**). Imagine reducing the scale of the solar system until the Sun is the size of a cherry, about 30 mm in diameter. Earth is located 3.2 m away, and is the size of a grain of salt (0.3 mm). The Moon, about 25 percent Earth's size, is orbiting it at a radius of about 1 cm. Jupiter, the largest planet, is an apple seed 17 m from the Sun. Neptune, at the edge of the planetary zone, is a grape seed (1.1 mm across) and almost 100 m from the central cherry. Your model solar system would be larger than two football fields, and you would need a powerful microscope to detect the asteroids orbiting between Mars and Jupiter. The planets are tiny specks of matter scattered around the Sun.

Revolution and Rotation

The planets revolve around the Sun in orbits that lie close to a common plane. Recall from Chapter 2 that *revolve* and *rotate* refer to different types of motion; a planet revolves around the Sun, but it rotates on its axis. The orbit of Mercury, the closest planet to the Sun, is tipped 7.0° to Earth's orbit. Remember that Earth's orbit defines the ecliptic plane, the reference plane for all other planetary orbits. The rest of the planets' orbital planes are inclined by no more than 3.4°. The solar system is basically flat and disk-shaped.

The rotation of the Sun and planets on their axes also seems related to the rotation of the disk. The Sun rotates with its equator inclined only 7.2° to the ecliptic plane, and most of the other planets' equators are tipped less than 30°. The rotations of Venus and Uranus are peculiar; Venus rotates backward compared with the other planets, and Uranus rotates on its side with its equator almost perpendicular to its orbit.

The preferred direction of motion in the solar system is counter-clockwise as seen from the north. All the planets revolve around the Sun in that direction, and all the planets also rotate on their axes in that direction—except Venus and Uranus, as mentioned above. Furthermore, nearly all the moons in the solar system, including Earth's moon, orbit around their respective planets in that same counter-clockwise direction.

Two Kinds of Planets

Perhaps the most striking clue to the origin of the solar system comes from the division of the planets into two groups, the small Earth-like worlds and the giant Jupiter-like worlds. The difference is so dramatic that we are inclined to say, "Aha, this must mean something!" In Chapter 12, this division into two groups of planets was an important clue for explaining how the Sun and the solar system formed 4.6 billion years ago.

The four inner planets—Mercury, Venus, Earth, and Mars—are small, dense worlds composed of rock and iron. They are called Terrestrial planets because they resemble the rock and metal composition of Earth (*Terra* in Latin). The four outer planets—Jupiter, Saturn, Uranus, and Neptune—are large, low-density worlds rich in hydrogen, water, and other low-density materials. They are known as Jovian planets because they are Jupiter-like (*Jove* in Latin). You could not stand on any of these planets as you can on any of the Terrestrial planets. You will study the Jovian worlds in the next chapter.

To begin your study of the five Terrestrial worlds—the Moon and the four inner planets—compare their features as shown in Figure 13.1. First notice their diameter. The Moon is small, and Mercury is not much bigger. Earth and Venus are large and similar in size, and Mars is a medium-sized world. You will discover that size is a key factor in determining a world's attributes; small worlds tend to be internally cold and geologically dead, but larger worlds can be geologically active.

Core, Mantle, and Crust

Notice that these Terrestrial worlds are made up of rock and metal. All of them are differentiated, with rocky, low-density crusts, high-density metal cores,

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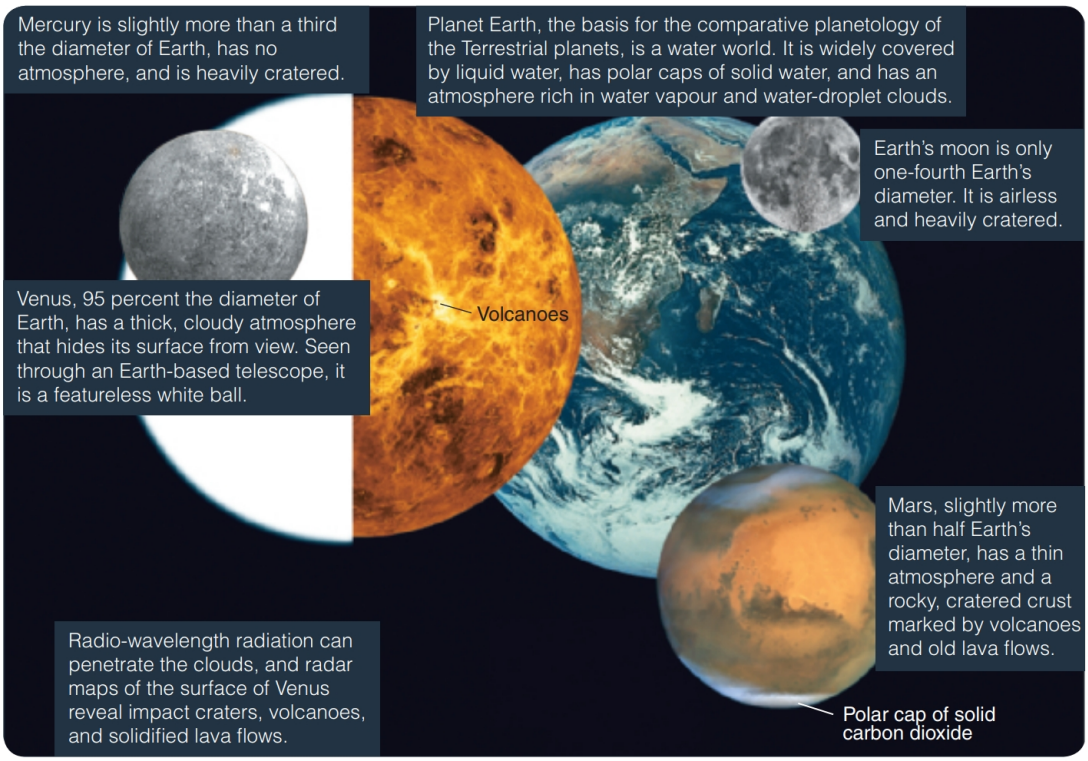


Figure 13.1 Planets in comparison. Earth and Venus are similar in size, but their atmospheres and surfaces are very different. The Moon and Mercury are much smaller, and Mars is intermediate in size.

and **mantles** composed of dense rock between the cores and crusts.

As you learned in Chapter 12, when the planets formed, their surfaces were subjected to heavy bombardment by leftover planetesimals and fragments; the cratering rate then was as much as 10000 times what it is at present. There are many craters on the Terrestrial worlds, especially on Mercury and the Moon. Notice that heavily cratered surfaces are old. For example, where a lava flow covered up some cratered landscape to make a new surface after the end of the heavy bombardment, very few craters could later be formed on that surface because most of the debris in the solar system was gone. When you see a smooth plain on a planet, you can assume that surface is younger than the cratered areas.

One important way to study a planet is by following its energy (see **How Do We Know? 13.1**). The heat in the interior of a planet may be what remained after the formation of the planet, or it may be heat generated by radioactive decay, but whatever its origin it must flow outward toward the cooler surface where it is radiated into space. In flowing outward, the heat can cause convection currents in the mantle, and can also cause magnetic fields, plate motions, quakes, faults, volcanism, mountain-building, and more. Heat flowing upward through the cooler crust makes a large world like Earth geologically active. In contrast, the Moon and Mercury, both small worlds, cooled fast, so they have very little heat flowing outward now and are relatively inactive.

Atmospheres

The atmospheres of the Terrestrial bodies are a study in contrasts. When you look at airless Mercury and the Moon in Figure 13.1, you can see their craters and plains and mountains, but the surface of Venus is completely hidden by a cloudy atmosphere much thicker than Earth's. Mars, the medium-sized Terrestrial planet, has a relatively thin atmosphere.

You might ponder two questions. First, why do some worlds have atmospheres while others do not? You will discover that both size and temperature are important. The second question is more complex. Where did these atmospheres come from? To answer that question, you need to study the geological history of these worlds.

mantle The layer of dense rock and metal oxides that lies between the molten core and Earth's surface, or a similar layer in another planet.

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HOW DO WE KNOW? 13.1



Understanding Planets: Follow the Energy

What causes change? One of the best ways to think about a scientific problem is to follow the energy. According to the principle of cause and effect, every effect must have a cause, and every cause must involve energy. Energy moves from regions of high concentration to regions of low concentration and, in doing so, produces changes. For example, coal burns to make steam in a power plant, and the steam passes through a turbine and then escapes into the air. In flowing from the burning coal to the atmosphere, the heat spins the turbine and makes electricity.

Scientists commonly use energy as a key to understanding nature. A biologist might ask where certain birds get the energy to fly thousands of kilometres, and a geologist might ask where the energy comes from to power a volcano. Energy is everywhere, and when it moves, whether it is in birds or molten magma, it causes change. Energy is the "cause" in "cause and effect."

The flow of energy from the inside of a star to its surface helps you know how the Sun and other stars work. The outward flow of energy supports the star against its own weight, drives convection currents that produce magnetic fields, and causes surface activity such as spots, prominences, and flares. You can understand stars by knowing how energy flows from their interiors to their surfaces and into space.



Michael A. Seeds

Heat flowing out of Earth's interior generates geological activity such as that at Yellowstone National Park.

Scientists think of a planet by following the energy. The heat in the interior of a planet may be left over from the formation of the planet, or it may be heat generated by radioactive decay, but it must flow outward toward the cooler surface, where it is radiated into space. In flowing outward, the heat can cause convection currents in the mantle, magnetic fields, plate motions, quakes, faults, volcanism, mountain building, and more.

When you think about any world, be it a small asteroid or a giant planet, think of its interior as a source of heat that flows through the planet's surface into space. When you follow that energy flow, you can understand a great deal about the world. A planetary astronomer once said, "The most interesting thing about any planet is how its heat gets out."

13.2 Earth: The Active Planet

You might wonder why you should study our very own planet. After all, you likely feel that we know everything there is to know about Earth. However, as alluded to earlier, Earth is the basis for your comparative study of the Terrestrial planets, so pretend to visit it as if you don't live here. It is an active planet with a molten interior and heat flowing outward that powers volcanism and earthquakes, and it has an active crust. Almost 75 percent of Earth's surface is covered by liquid water, and the atmosphere contains a significant amount of oxygen.

Earth's Interior

From what you know of the formation of Earth (see Chapter 12) you can expect it to have differentiated, but what does the evidence reveal about Earth's interior?

Earth's average density is about 5.5 g/cm^3, but the density of Earth's rocky crust is only about half that. Clearly, a large part of Earth's interior must be made of material denser than rock.

Each time an earthquake occurs, seismic waves travel through the interior and register on seismographs all over the world. Analysis of these waves shows that Earth's interior is divided into a metallic core, a dense rocky mantle, and a thin, low-density crust. The core has a density of 14 g/cm^3, denser than lead; mathematical models

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indicate it is composed of iron and nickel at a temperature of roughly 6000 K. Thus you see that the core of Earth is as hot as the gaseous surface of the Sun, but high pressure keeps the metal a solid near the middle of the core and a liquid in its outer parts.

Earth's magnetism gives further clues about the core. The presence of a magnetic field is evidence that part of Earth's core must be a liquid metal. Convection currents stir the molten liquid, and because it is a very good conductor of electricity and is rotating as Earth rotates, it generates a magnetic field through the dynamo effect—a different version of the process that creates the Sun's magnetic field (see Chapter 5).

Earth's mantle is a deep layer of dense rock that lies between the molten core and the solid crust. Models indicate the mantle material has the properties of a solid but is capable of flowing slowly, like asphalt used in paving roads, which shatters if struck with a sledgehammer but bends slightly under the weight of a truck. Just below Earth's crust, where the pressure is less than at greater depths, the mantle flows most easily.

Earth's rocky crust is made up of low-density rocks floating on the higher-density mantle like great lily pads floating on a pond. The crust is thickest under the continents, up to 60 km thick, and thinnest under the oceans, where it is only about 10 km thick.

Earth's Active Crust

The motion of the crust and the erosive action of water make Earth's crust highly active and changeable. As you study **Visualizing Astronomy 13.1, The Active Earth**, you should notice three important points:

1. The motion of crustal plates produces much of the geological activity on Earth. Earthquakes, volcanism, and mountain building are linked to motions in the crust and the location of plate boundaries. While thinking about volcanoes, you can correct a common misconception. The molten rock that emerges from volcanoes comes from pockets of melted rock in the upper mantle and lower crust, not from the molten core.
2. The continents on Earth's surface have moved and changed over periods of hundreds of millions of years. A hundred million years is only 0.1 billion years, roughly 2% of the age of Earth, so sections of Earth's crust are in rapid motion, geologically.
3. Most of the geological features you know—the Rocky Mountains, the Great Lakes, and even the outline of the continents—are recent products of Earth's active surface.

Earth's surface is constantly renewed, and small crystals called zircons are the oldest known Earth material. They are from Western Australia and are 4.4 billion years old. Most of the crust is much younger than that. The mountains and valleys you see around you are probably no more than a few tens or hundreds of millions of years old.

Earth's Atmosphere

When you think about Earth's atmosphere, consider three questions: How did it form? How has it evolved? How are humans changing it? Answering these questions will help you understand other planets as well as our own.

Our planet's first atmosphere, its **primary atmosphere**, was once thought to contain gases captured from the solar nebula, such as hydrogen and methane. Modern studies, however, indicate that the planets were hot when they formed, so gases such as carbon dioxide, nitrogen, and water vapour were outgassed from the rock and metal (see Chapter 12). In addition, the final stages of planet building may have seen Earth and the other planets accreting planetesimals rich in volatile materials, such as water, ammonia, and carbon dioxide. Thus, the primary atmosphere must have been rich in carbon dioxide, nitrogen, and water vapour. The atmosphere you breathe today is a **secondary atmosphere**, produced later in Earth's history.

Soon after Earth formed, it began to cool; once it cooled enough, oceans began to form, and carbon dioxide began to dissolve in the water. Carbon dioxide is highly soluble in water, which explains the easy manufacture of carbonated beverages. As the oceans removed carbon dioxide from the atmosphere, the carbon dioxide reacted with dissolved compounds in the ocean water to form silicon dioxide, limestone, and other mineral sediments. Consequently, the oceans transferred carbon dioxide from the atmosphere to the sea floor and left the air richer in other gases, especially nitrogen.

That removal of carbon dioxide is critical to Earth because an atmosphere rich in carbon dioxide can trap heat by a process called the **greenhouse effect**. When visible-wavelength sunlight shines through the glass roof of a greenhouse, it heats the interior. Infrared radiation from the warm interior can't get out through the glass,

primary atmosphere A planet's first atmosphere.

secondary atmosphere A planet's atmosphere that replaces the primary atmosphere—for example, due to outgassing, the impact of volatile-bearing planetesimals, or biological activity.

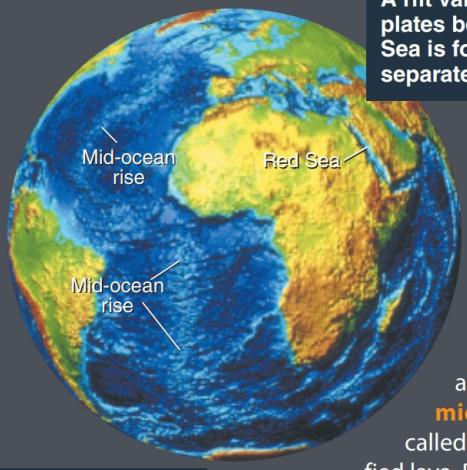
greenhouse effect The process by which a carbon dioxide atmosphere traps heat and raises the temperature of a planetary surface.

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Visualizing Astronomy 13.1
THE ACTIVE EARTH

1

Our world is an astonishingly active planet. Not only is it rich in water and therefore subject to rapid erosion, but its crust is divided into moving sections called *plates*. Where plates spread apart, lava wells up to form new crust; where plates push against each other, they crumple the crust to form mountains. Where one plate slides over another, you see volcanism. This process is called **plate tectonics**, referring to the Greek word for "builder." (An architect is literally an arch builder.)



A rift valley forms where continental plates begin to pull apart. The Red Sea is forming as Africa starts to separate from the Arabian peninsula.

National Geophysical Data Center



A typical view of planet Earth

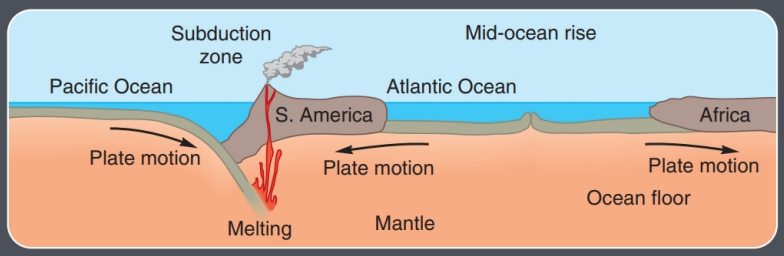
William K. Hartmann/ Planetary Science Institute

Courtesy Janet Seeds

Mountains are common on Earth, but they erode away rapidly because of the abundant water.

1a Evidence of plate tectonics was first found in ocean floors, where plates spread apart and magma rises to form **mid-ocean rises** made of rock called **basalt** that is typical of solidified lava. Radioactive dating shows that the basalt is younger near the mid-ocean rise. Also, the ocean floor carries less sediment near the mid-ocean rise. As Earth's magnetic field reverses back and forth, it is recorded in the magnetic fields frozen into the basalt. This produces a magnetic pattern in the basalt that shows that the sea floor is spreading away from the mid-ocean rise.

1b A **subduction zone** is a deep trench where one plate slides under another. Melting releases low-density magma that rises to form volcanoes such as those along the northwest coast of North America, including Mount Ranier.



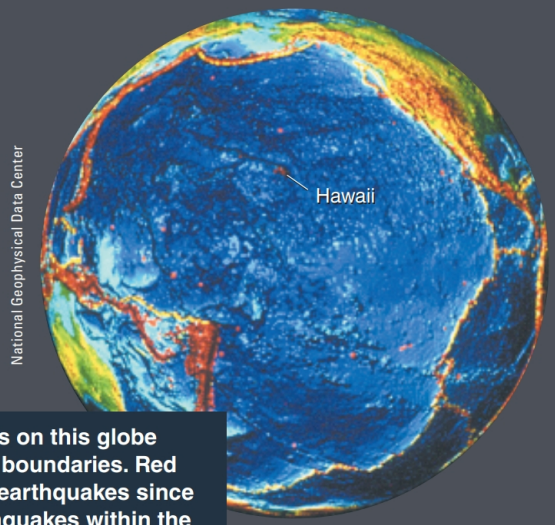
1c Hot spots caused by rising magma in the mantle can poke through a plate and cause volcanism such as that in Hawaii. As the Pacific plate has moved northwestward, the hot spot has punched through to form a chain of volcanic islands, which are now mostly worn below sea level. **Folded mountain ranges** can form where plates push against each other. For example, the Ural Mountains lie between Europe and Asia, and the Himalaya Mountains are formed by India pushing north into Asia. The Appalachian Mountains are the remains of a mountain range thrust up when North America was pushed against Europe and Africa.



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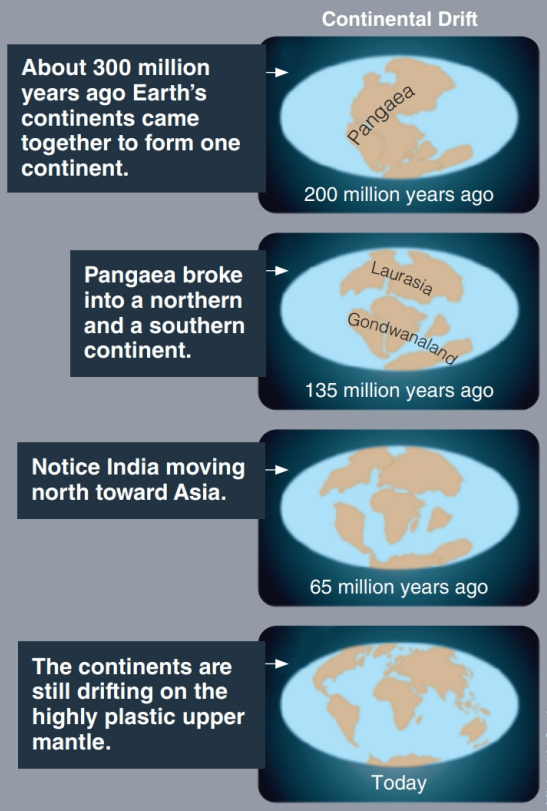
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1d The floor of the Pacific Ocean is sliding into subduction zones in many places around its perimeter. That process pushes up mountains such as the Andes and triggers earthquakes and active volcanism all around the Pacific in what is called the Ring of Fire. In places such as California, the plates slide past each other, causing frequent earthquakes.



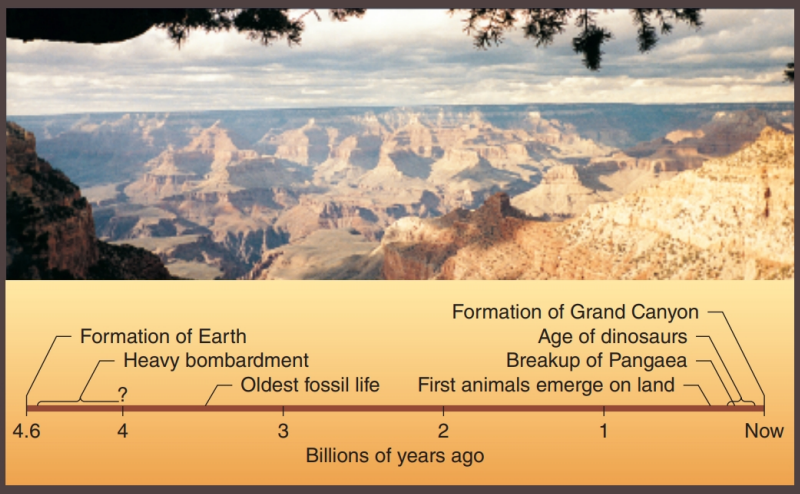
National Geophysical Data Center

Yellow lines on this globe mark plate boundaries. Red dots mark earthquakes since 1980. Earthquakes within the plate, such as those at Hawaii, are related to volcanism over hot spots in the mantle.



Michael A. Seeds

2 The floor of the Atlantic Ocean is not being subducted. It is locked to the continents and is pushing North and South America away from Europe and Africa at about 3 cm per year in a motion called *continental drift*. Scientists can measure the motion by, for example, comparing the time for laser flashes sent from European and American observatories to bounce off mirrors left on the Moon by the *Apollo* astronauts. Roughly 200 million years ago, North and South America were joined to Europe and Africa. Evidence of that lies in similar fossils and similar rocks and minerals found in the matching parts of the continents.



Michael A. Seeds

3 Plate tectonics push up mountain ranges and cause bulges in the crust, and water erosion wears the rock away. The Colorado River began cutting the Grand Canyon only about 10 million years ago when the Colorado plateau warped upward under the pressure of moving plates. That sounds like a long time ago, but it is only 0.01 billion years. A kilometre and a half down, at the bottom of the canyon, lie rocks 0.57 billion years old, the roots of an earlier mountain range that stood as high as the Himalayas. It was pushed up, worn away to nothing, and covered with sediment long ago. Many of the geological features we know on Earth have been produced by relatively recent events.

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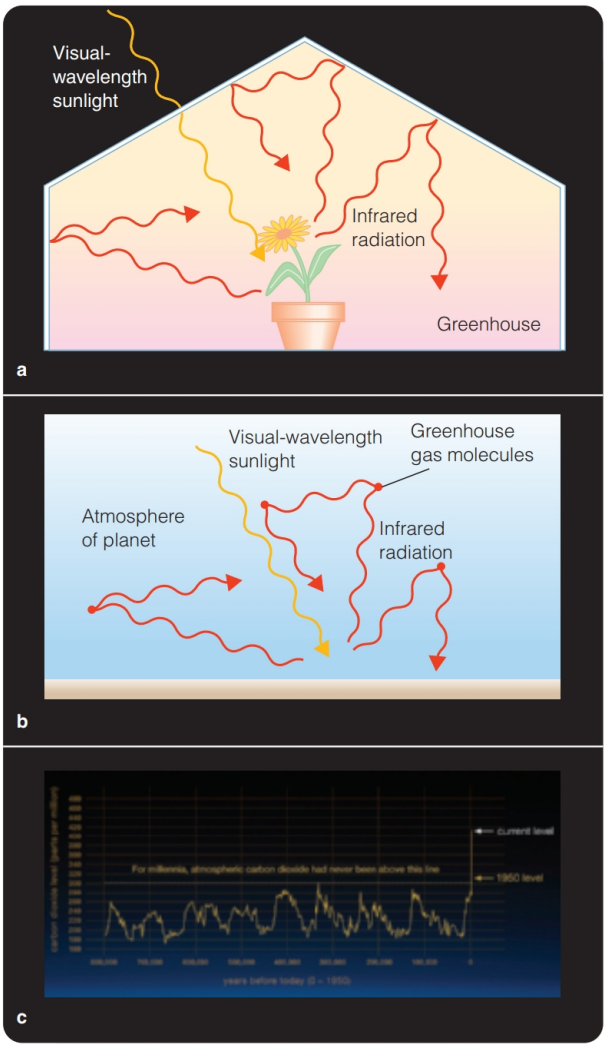
heat is trapped in the greenhouse, and the temperature climbs until the glass itself grows warm enough to radiate heat away as fast as sunlight enters (see Figure 13.2a). This is also called the "parked car effect," for obvious reasons.

Like the glass roof of a greenhouse, a planet's atmosphere can allow sunlight to enter and warm the surface. Note the similarity between the flow of light into the greenhouse in Figure 13.2a and into the atmosphere in Figure 13.2b. Carbon dioxide and other greenhouse gases such as water vapour and methane are opaque to infrared radiation, so an atmosphere containing enough of these greenhouse gases can trap heat and raise the temperature of a planet's surface.

It is a common misconception that the greenhouse effect is always bad. Without the greenhouse effect, Earth would be colder by at least 30°C, with a planet-wide average temperature far below freezing. The problem is that human civilization is adding greenhouse gases to those that were already in the atmosphere. For 4 billion years, Earth's oceans and plant life have been absorbing carbon dioxide and burying it in the form of carbonates such as limestone and in carbon-rich deposits of coal, oil, and natural gas. In the last century or so, human civilization has begun digging up those fuels, burning them for energy, and releasing the carbon back into the atmosphere as carbon dioxide (Figure 13.2c). This process is steadily increasing the carbon dioxide concentration in the atmosphere and warming Earth's climate in what is called **global warming**. Evidence based on the proportions of carbon isotopes and oxygen in the atmosphere shows that most of the added CO_2 is the result of burning fossil fuels. There is now overwhelming evidence that humans are responsible for the increase in atmospheric greenhouse gases. The UN Intergovernmental Panel on Climate Change (IPCC) stated in its September 2013 report that "there is 95 percent certainty that humans have caused most of the warming of the planet's surface that has occurred since the 1950s." Over the past century, the average surface temperature has risen by almost 1°C.

Global warming is a critical issue not just because it affects agriculture. It changes climate patterns by warming some areas and cooling other areas. In addition, the warming is melting permanently frozen ice in the polar caps, causing sea levels to rise. A rise of just a metre will flood major land areas. It is very clear that humanity has the capacity and ability to significantly affect the planet's climate. When you study Venus, you will see a planet dominated by a runaway greenhouse effect.

global warming The gradual increase in the surface temperature of Earth caused by human modifications to Earth's atmosphere.



(a) and (b) © Cengage Learning; (c) Luthi, D., et al.. 2008; Etheridge, D.M., et al. 2010; Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO_2 record. NASA

Figure 13.2 The greenhouse effect. (a) Visual-wavelength sunlight can enter a greenhouse and heat its contents, but the longer-wavelength infrared radiation cannot get out. (b) The same process can heat a planet's surface if its atmosphere contains greenhouse gases such as CO_2. (c) The concentration of CO_2 in Earth's atmosphere as measured in ice cores remained roughly constant at an average level of 240 ppm for thousands of years until the beginning of the Industrial Revolution around the year 1800. Since then it has increased by more than 40 percent. In 2013, CO_2 levels rose above 400 ppm for the first time in recorded history. (Note that the bottom of the vertical scale is not at zero.)

Oxygen in Earth's Atmosphere

When Earth was young, its atmosphere had no free oxygen. Oxygen is very reactive and quickly forms

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oxides in the soil, so the activity of plant life is needed to keep a steady supply of oxygen in the atmosphere. Photosynthesis makes energy for the plant by absorbing carbon dioxide and releasing free oxygen. About 2 to 2.5 billion years ago plants began to produce oxygen faster than chemical reactions could remove it from the atmosphere. Atmospheric oxygen then increased rapidly.

Because there is oxygen (O_2) in the atmosphere now, there is also a layer of ozone (O_3) at altitudes of 15 to 30 km. Many people hold the common misconception that ozone is bad because they hear it mentioned as part of smog. Breathing ozone is bad for you, but we need the ozone layer in the upper atmosphere to protect us from harmful UV photons. Certain compounds called chlorofluorocarbons (CFCs) used in refrigeration and industry can destroy ozone when they leak into the atmosphere. In the mid 1970s research revealed that the ozone layer was being depleted largely by the use of CFCs, raising concerns that enhanced UV levels would be disastrous to human life. Since then most of Earth's countries have agreed to a treaty banning the use of ozone-depleting chemicals. Recent measurements indicate that the depletion rate has slowed or perhaps even stopped. However, it will take over one hundred years for the ozone layer to return to pre-1970 levels. Understand that ozone depletion is an additional Earth environmental issue that is separate from global warming. While this poses an immediate problem for public health, it is also of interest astronomically. When you study Mars, you will see the effects of an atmosphere without ozone.

A Short Geological History of Earth

As Earth formed in the inner solar nebula, it passed through three stages that also describe the histories of the other Terrestrial planets to varying extents. When astronomers try to tell the story of each planet in our solar system, they pull together all the known facts and hypotheses and try to make them into a logical history of how the planet got to be the way it is. Of course, these stories are incomplete because scientists don't yet understand all the factors affecting the history of the planets.

The first stage of planetary evolution is *differentiation*, the separation of each planet's material into layers according to density. Some of that differentiation may have occurred very early as the heat released by infalling matter melted the growing Earth. Some of the differentiation, however, may have occurred later as radioactive decay released more heat and further melted Earth, allowing the denser metals to sink to the core.

The second stage, *cratering and giant basin formation*, could not begin until a solid surface formed. The heavy bombardment in the early solar system cratered Earth just as it did the other Terrestrial planets. Some of

CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



THE CANADIAN PRESS/Bill Becker

Roberta Bondar

Roberta Bondar

In January 1992, Dr. Roberta Bondar made history. When she launched from Earth in the space shuttle *Discovery*, she became Canada's first woman in space and the world's first neurologist-astronaut. As a young girl she had envied birds for being able to fly and had dreamed of being an astronaut. Her interest in science was encouraged by her parents, who built her a laboratory in their basement. This fuelled her passion for science, and after obtaining undergraduate and master's degrees in zoology and pathology, she obtained a Ph.D. in neuroscience at the University of Toronto and an M.D. from McMaster University, thus becoming both a scientist and a doctor by age 31. She then added "astronaut" to her list of occupations when in 1983 she was selected to be part of the first Canadian Astronaut Program and became the payload specialist for the first International Microgravity Laboratory Mission. During her mission in space in 1992, she conducted experiments for 14 countries. After returning to Earth, she headed an international research team at NASA that investigated the effects of exposure to space on the human body. Dr. Bondar is also an accomplished photographer and a passionate advocate for environmental education and protection. The Roberta Bondar Foundation educates people about the environment by combining photography and science. Dr. Bondar has been awarded the NASA Space Medal and the Order of Canada, and has been inducted into the Hall of Fame of the International Women's Forum.

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the largest craters, called basins, were likely big enough to break through to the upper mantle where rocks are partly molten. The molten rock would have welled up through cracks to fill some of the basins and craters. On planets with liquid water, the basins may also have been the first oceans. As the debris of planet formation cleared away, the rate of impacts and crater formation fell to its present low rate.

The third stage, *slow surface evolution*, has continued for at least the past 3.5 billion years. Earth's surface is constantly changing as sections of crust slide over and past each other, push up mountains, and shift continents. In addition, moving air and water erode the surface and wear away geological features. Almost all traces of the earlier stages of differentiation and cratering have been destroyed by the active crust and erosion. Life apparently started on Earth around the beginning of the slow surface evolution stage, and the secondary atmosphere began to replace the primary atmosphere. That may be unique to Earth and may not have happened on the other Terrestrial planets.

Terrestrial planets pass through these stages, but differences in masses, temperature, and composition emphasize some stages over others and produce surprisingly different worlds.

13.3 The Moon

The Moon is our constant companion and visible during both the day and the night. We know the Moon is too small to have retained any atmosphere, so strolling on the surface requires a spacesuit similar to that used by the lunar astronauts. As well, plans for such exploration need to take into account the fact that the temperature difference from sunshine to shade is extreme. Review the Moon's data in the **Celestial Profiles** in Appendix C.

maria Lunar lowlands filled by successive flows of dark lava; from the Latin for *sea*.

albedo The ratio of the amount of light reflected from an object to the amount of light received by the object. Albedo equals 0 for perfectly black and 1 for perfectly white.

ejecta Pulverized rock scattered by meteorite impacts on a planetary surface.

anorthosite Aluminium- and calcium-rich silicate rock found in the lunar highlands.

breccia Rock composed of fragments of older rocks bonded together.

Lunar Geology

There are two kinds of terrain on the Moon. The dark grey areas visible from Earth are smooth lunar lowlands, which astronomers have named **maria** (plural of *mare*, pronounced mah-ray), drawing on the Latin word for "seas." The lighter-coloured regions are mountainous lunar highlands. The Moon looks quite bright in the night sky seen from Earth. In fact, the **albedo** of the near side of the Moon is only 0.12, meaning it reflects only 12 percent of the light that hits it. The Moon looks bright only in contrast to the night sky. In reality, it is a dark grey world.

Wherever you go on the Moon, you will find craters. The highlands are marked heavily by craters, but the smooth lowlands contain fewer craters. The craters on the Moon were formed by impacts, as evidenced by their distinguishing characteristics such as shape and the material (**ejecta**) they have spread across the Moon's surface. Craters range in size from giant basins hundreds of kilometres across to microscopic pits found in Moon rocks. Most of the craters on the Moon are old. A comparison of the ages of Moon rocks collected from both the heavily cratered highlands and also the somewhat younger, less heavily cratered maria clearly shows that the craters were formed long ago when the solar system was young.

Twelve American astronauts from *Apollo* missions visited both the Moon's maria and the highlands in six expeditions between 1969 and 1972 (Figure 13.3). Most of the rocks they found in both the highlands and the maria were typical of hardened lava. The maria are actually ancient basalt lava flows. In contrast, the highlands are composed of low-density rock: for example **anorthosite** (a light-coloured rock that contributes to the brightness of the highlands compared to the darkness of the maria) would have been among the first material to solidify and float to the top of molten rock. Many rocks found on the Moon are **breccias**, made up of fragments of broken rock cemented together under pressure. The breccias show how extensively the Moon's surface has been shattered by meteorites, as does the surface layer of powdery dust kicked up by the astronauts' boots.

The Origin of Earth's Moon

Over the last two centuries, astronomers developed three hypotheses for the origin of Earth's moon. The *fission hypothesis* proposed that the Moon broke from a rapidly spinning proto-Earth. The *condensation hypothesis* suggested that Earth and its Moon condensed from the same cloud of matter in the solar nebula. The *capture hypothesis* suggested that the Moon formed elsewhere in the solar nebula and was later captured by Earth. Each of these earlier ideas had problems and failed to survive when all the evidence was compared.

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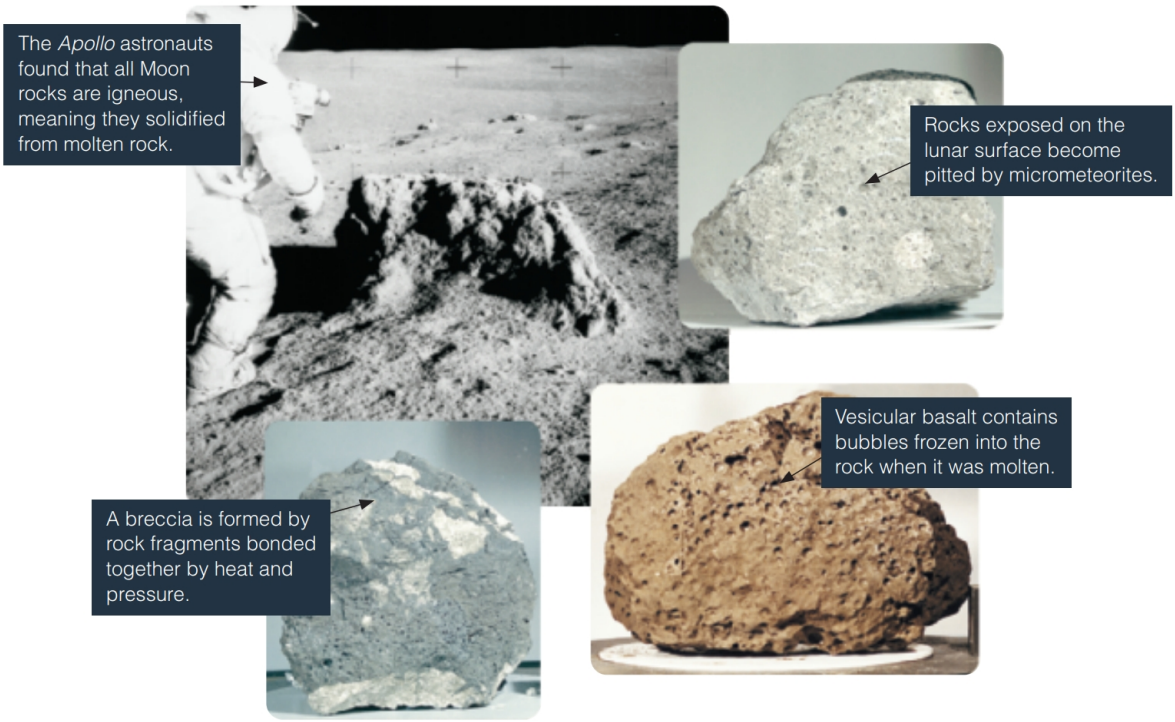


Figure 13.3 Rocks from the Moon show that the Moon's surface formed in a molten state, that it was heavily fractured by cratering when it was young, and that it is now affected mainly by micrometeorite erosion.

In the 1970s, a new hypothesis was proposed that combined some aspects of the three previous hypotheses. The **large-impact hypothesis** proposes that the Moon formed when a planetesimal, estimated to have been at least as large as Mars, smashed into the proto-Earth. Model calculations indicate that this collision would have ejected a disk of debris into orbit around Earth and that would have quickly formed the Moon (Figure 13.4).

This hypothesis explains a number of phenomena. If the collision had occurred off-centre, it would have spun the Earth–Moon system rapidly, and this would explain its present high angular momentum. If the proto-Earth and its impactor both had already differentiated, the ejected material would have been mostly iron-poor mantle and crust, and this would explain the Moon's low density and iron-poor composition. Furthermore, the material would have lost many of its volatile components while it was in space, so the Moon would have formed lacking those materials. Such an impact would have melted the proto-Earth, and the material falling together to form the Moon would have been heated hot enough to melt. This fits the evidence that the highland anorthosite in the Moon's oldest rocks formed by differentiation of large quantities of molten material. The large-impact hypothesis passes tests of comparison with the known evidence and is now considered likely to be correct.

The History of Earth's Moon

The history of Earth's moon since its formation is dominated by a single fact—the Moon is small, only one-quarter the diameter of Earth. The escape velocity is low, so it has been unable to hold any atmosphere, and it cooled rapidly as its internal heat flowed outward into space.

The Moon rocks from the *Apollo* missions are a great source of information about the timing of events during the Moon's history. For example, they show that the Moon must have formed in a mostly molten state. Planetary geologists now refer to the exterior of the newborn Moon as a **magma ocean**. Denser materials sank toward the centre, and low-density minerals floated to the top to form a low-density crust. In this way the Moon partly differentiated. The radioactive ages of the Moon rocks show that the surface solidified about 4.4 billion years ago.

large-impact hypothesis Hypothesis that the Moon formed from debris ejected during a collision between Earth and a large planetesimal.

magma ocean The exterior of the newborn Moon, a shell of molten rock hundreds of kilometres deep.

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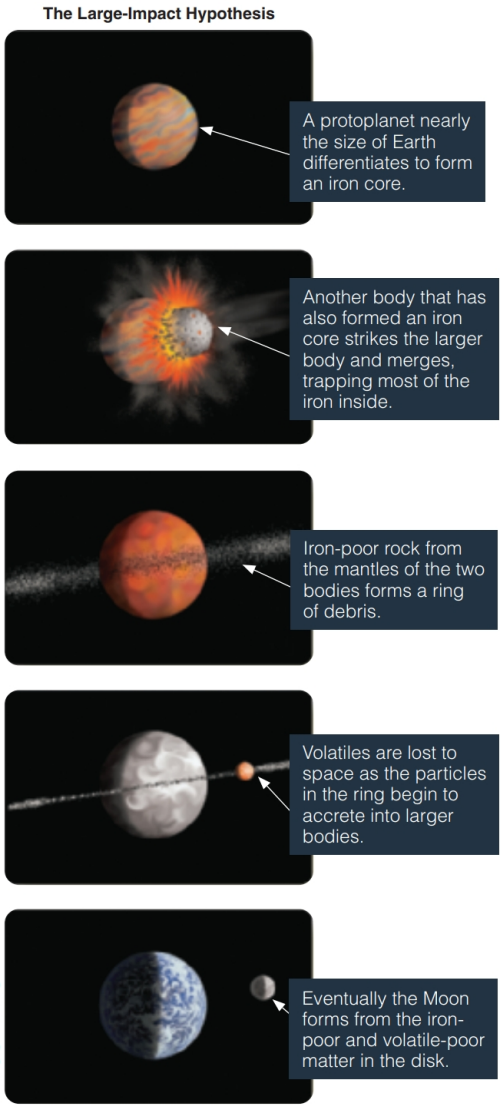


Figure 13.4 The large-impact hypothesis. The large-impact hypothesis holds that when the solar system was about 50 million years old, a massive collision produced the Moon in its orbit inclined to Earth's equator.

multiringed basin Large impact feature (crater) containing two or more concentric rims formed by fracturing of the planetary crust.

late heavy bombardment The sudden, temporary increase in the cratering rate in our solar system that occurred about 4 billion years ago.

micrometeorite Meteorite of microscopic size.

The second stage, cratering and basin formation, began as soon as the crust solidified, and the older highlands show that cratering was intense for approximately 0.5 billion years, during the heavy bombardment at the end of the solar system's period of planet-building. The Moon's crust was shattered, and the largest impacts formed giant **multiringed basins** hundreds of kilometres in diameter (Figure 13.5). Some evidence indicates that roughly 4 billion years ago there was a sudden, temporary increase in the cratering rate. Astronomers refer to this as the **late heavy bombardment** period and speculate that it could have been caused by the final accretion and migration of Uranus and Neptune (see Chapter 12) scattering remnant planetesimals across the solar system to collide with the Moon and planets. About 3.8 billion years ago the cratering rate fell rapidly to the current low rate.

The tremendous impacts that formed the lunar basins cracked the crust as deep as 10 kilometres and led to flooding by lava. Though Earth's moon cooled rapidly after its formation, radioactive decay heated the subsurface material, and part of it melted, producing lava that followed the cracks up into the giant basins (Figure 13.5). Studies of rocks brought back from the Moon by *Apollo* astronauts show that the basins were flooded by successive lava flows of dark basalts from roughly 4 to 2 billion years ago, forming the maria. The Moon's crust is thinner on the side toward Earth, perhaps due to tidal effects. Consequently, while lava flooded the basins on the Earth-facing side, it was unable to rise through the thicker crust to flood the lowlands on the far side.

The third stage, slow surface evolution, was limited both because the Moon cooled rapidly and because it lacks water. Flooding on Earth included water, but the Moon has never had an atmosphere and thus has never had liquid water. With no air and no water, erosion is limited to the constant bombardment of **micrometeorites** and rare, larger impacts. Indeed, a few meteorites found on Earth have been identified as rocks ejected from the Moon by impacts within the last few million years. As the Moon lost its internal heat, volcanism died down, and the Moon became geologically dead. Its crust never divided into moving plates (there are no folded mountain ranges) and the Moon is now a "one-plate" planet.

Exploration

One of the greatest expeditions humans ever undertook occurred in July 1969, when American astronauts travelled to the Moon, landed safely, walked on the Moon's surface for the first time, and returned to Earth. Between 1969 and 1972, NASA's *Apollo* program, which involved scientists from around the world, including Canada, landed 12 humans on the Moon. *Apollo 11*, launched on July 16, 1969, successfully landed Edwin (Buzz) Aldrin and Neil Armstrong on the lunar surface on July 20, 1969.

The mission, although extremely inspirational, was a dangerous one that almost ended in tragedy. The first stage involved being hurled toward the Moon by enormous Saturn V rockets. These rockets, designed by German-born scientist

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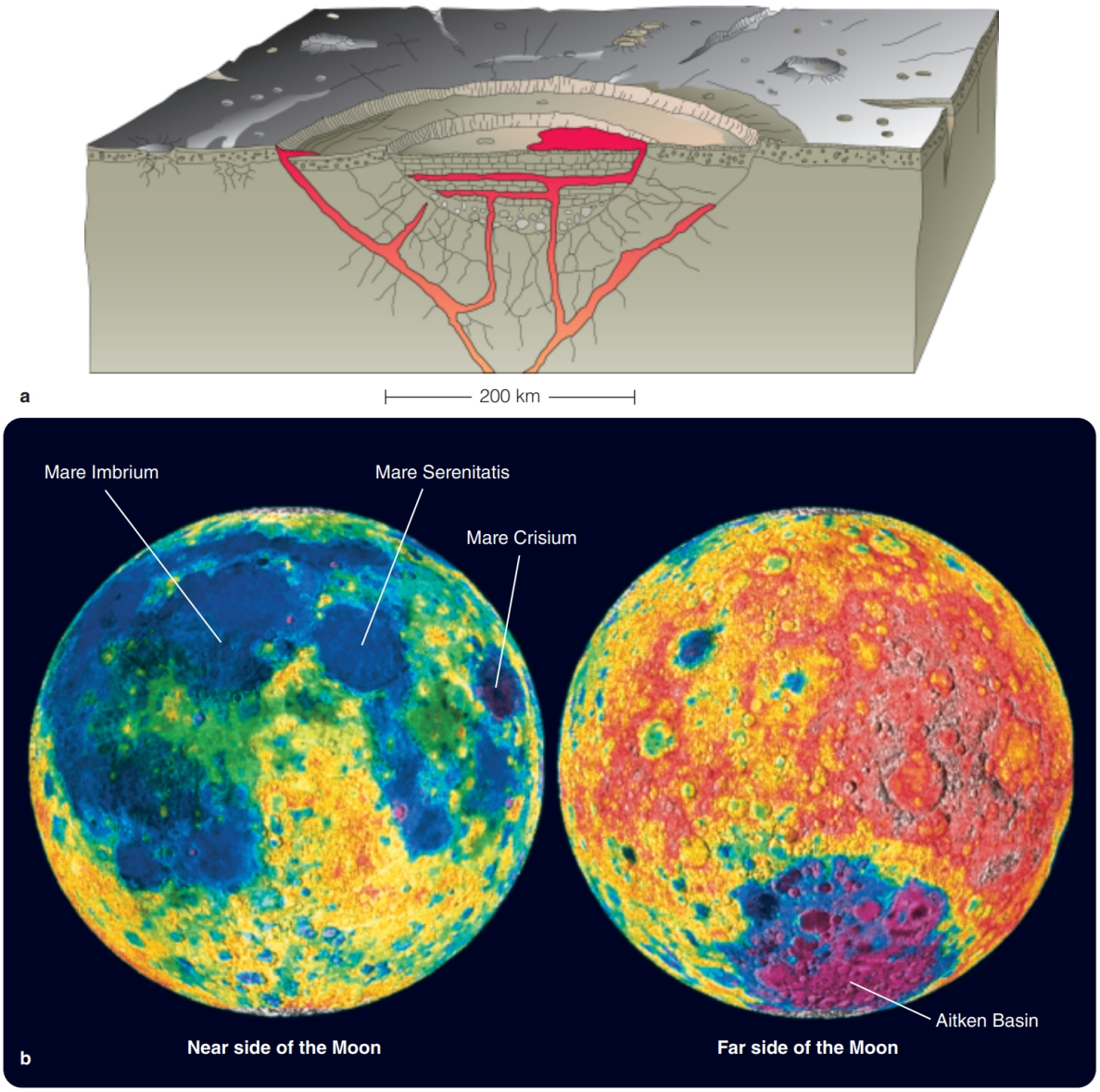


Figure 13.5 Much of the near side of the Moon is marked by great, generally circular lava plains called maria. The crust on the far side is thicker, and there was much less flooding. Even the huge Aitken basin near the lunar south pole contains little lava flooding. In these maps colour marks elevation, with red the highest regions and purple the lowest.

Wernher von Braun, were the most powerful rockets ever built and held millions of litres of highly explosive fuel. A single stray spark could have caused a disastrous explosion.

The most complicated stage after launch was the landing process on the Moon. The lunar lander's computer system was the most sophisticated at that time but had the computing power of today's basic calculator, and was overloaded during landing with two minutes of fuel left in the descent engine's tank. At this stage, the computer's landing target was a rocky area, but Armstrong managed to manually land the craft in a crater with only about 15 seconds of fuel left.

After the eventful landing, the crew was unable to sleep and decided to venture out onto the Moon's surface. This proved problematic as well because the hatch door would not open due to the pressure difference. Eventually, Aldrin was able to bend the door and equalize the pressure, allowing the astronauts to take their first historic steps on the lunar surface. The crew proceeded to collect soil samples and conduct the first-ever experiments on the Moon.

The final problem was one that could have left the crew stranded on the Moon forever: a circuit breaker essential to the functioning of the lander's engine broke

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off. The crew had no spare parts, so Aldrin used a pen to push the circuit breaker in and get the engine started.

Finally, the astronauts were able to rendezvous with the orbiter, and they made the long trip home to Earth. Their story of courage and innovation in the face of disaster remains an inspiration for humanity's future expeditions to space.

13.4 Mercury

Like Earth's moon, Mercury is small and nearly airless. Being the closest planet to the Sun, it is visible either at dawn near the eastern horizon or at dusk near the western horizon. It has a moderately high eccentric orbit, whose orbital plane is the highest of all the modern planets at 7°. Mercury's orbital period is 88 days, but its rotation is relatively slow, resulting in a solar day that is 176 Earth days long. Mercury cooled too quickly to develop plate tectonics, so it is a cratered, dead world. Consult **Celestial Profiles** in Appendix C for more data on Mercury.

A History of Mercury

The fact that Mercury is small has determined much of its history. Not only is Mercury too small to retain an atmosphere but also it has lost much of its internal heat; therefore, it is not geologically active.

Early in its formation, Mercury differentiated to form a metallic core and a rocky mantle. The presence of a magnetic field is evidence of a large metallic core. Astronomers thought for decades that Mercury has a lot of iron because it formed near the Sun where rock is less stable, but detailed calculations show that Mercury contains even more iron than expected. Drawing on the large-impact hypothesis for the origin of Earth's moon, scientists proposed that Mercury suffered a major impact that shattered and drove away much of the rocky mantle. However, data from the *MESSENGER* spacecraft indicate that the crust contains significant volatiles that would not have survived a giant impact. So a giant impact may not, after all, explain Mercury's large metal core.

In the second stage of planet formation, cratering battered the crust, and lava flows welled up to fill the lowlands, just as they did on the Moon. As the small world lost internal heat, its large metal core contracted, and its crust compressed and broke to form the long ridges, much as the peel of a drying apple wrinkles.

Lacking an atmosphere to erode it, Mercury has changed little since the last lava hardened, and it is now a single-plate planet like Earth's moon.

Exploration

Mercury orbits close to the Sun and is difficult to observe from Earth. Consequently, little was known until 1974–1975, when the *Mariner 10* spacecraft flew past Mercury three times and revealed a planet with a heavily cratered surface, much like that of Earth's moon (see Figure 13.6). More recently, a spacecraft called *MESSENGER* made three flybys of Mercury in 2008 and 2009, taking impressive high-resolution images and measurements of the parts of the planet not covered by *Mariner 10*'s cameras. *MESSENGER* went into orbit around Mercury in March 2011 and began an extended, close-up study. Analysis shows that large areas were once flooded by lava and then cratered. The largest impact feature on Mercury is the Caloris Basin, a multiringed area 1500 km in diameter (Figure 13.7).

Mercury is quite dense, and models indicate that it must have a large metallic core. In fact, the metallic core occupies about 70 percent of the radius of the planet. Mercury is essentially a metal planet with a thin rock mantle. *Mariner 10* photos reveal long curving ridges up to 3 km high and 500 km long (see Figure 13.6). The ridges even cut through craters, which indicates they formed after most of the heavy bombardment. Planetary scientists understand these ridges as evidence that long ago Mercury shrank as it cooled and its crust wrinkled to form the curving ridges. During *MESSENGER*'s time in orbit, four major discoveries have been made that have put early theories of Mercury's formation into doubt: (a) the planet's global magnetic field, although only 1 percent as strong as Earth's, is strangely misaligned with Mercury's rotational axis, which is offset from its north pole by almost 500 km; (b) Mercury's surface composition contains much more magnesium, sodium, and sulphur and far less aluminum and iron than either Earth or the Moon; (c) there is strong evidence for water ice existing deep in the permanently shadowed craters around both



NASA

Figure 13.6 The first spacecraft to visit Mercury, *Mariner 10*.

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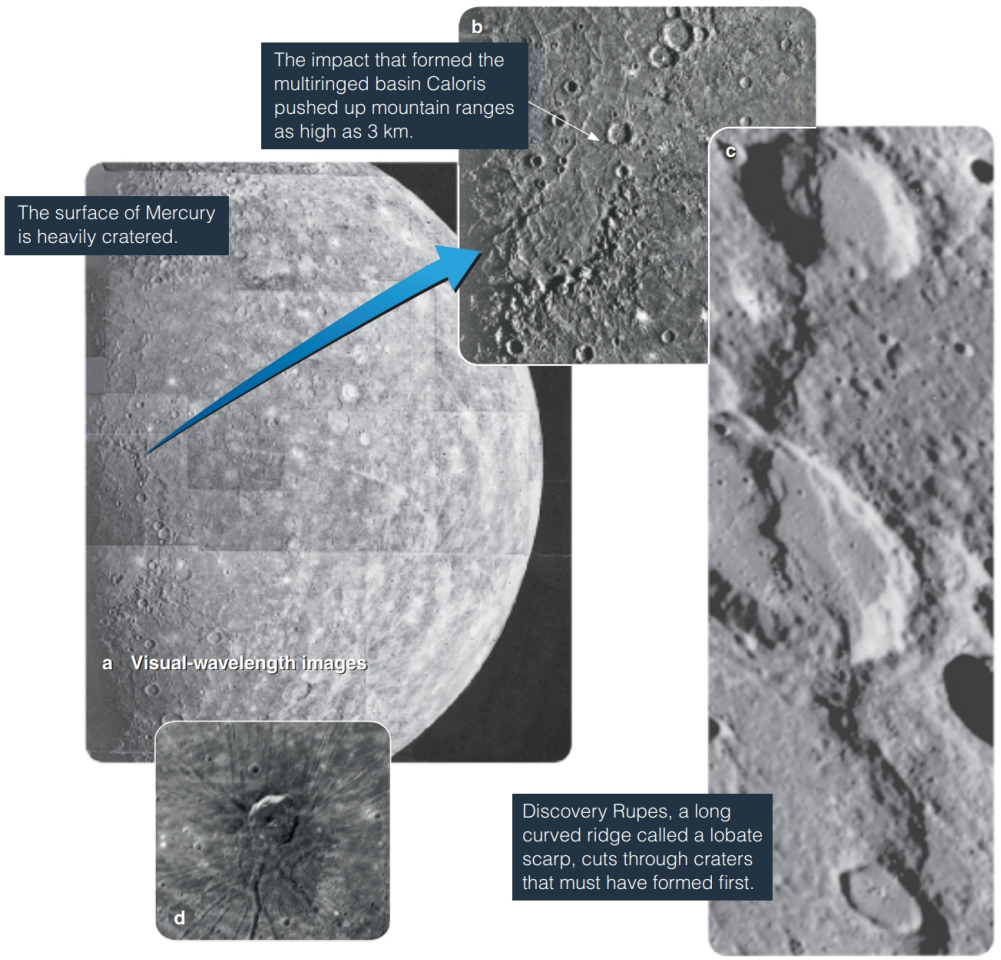


Figure 13.7 (a) Mercury is an airless, cratered world. (b) The Caloris multiringed basin was half in shadow and half in sunlight when the *Mariner 10* spacecraft flew past the planet. (c) Lobate scarps are distributed all around Mercury. (d) The origin of the spider formation photographed by *MESSENGER* is a puzzle.

north and south poles; and (d) low-altitude images showing small fault scarps (landforms resembling stair steps) from which scientists conclude that Mercury is still contracting and, therefore, still cooling. Having exhausted all of its propellant used to make orbital adjustments, *MESSENGER* crashed into Mercury's surface in April 2015.

Spacecraft *BepiColombo*, a joint European–Japanese mission, is now on its way to Mercury and is expected to begin orbiting in 2024. Planned studies include surface and interior compositions and Mercury's magnetosphere.

13.5 Venus

You might expect Venus to be much like Earth. Its diameter is 95 percent that of Earth's, its average density is similar, and it is only 30 percent closer to the Sun. However, because of a **runaway greenhouse effect** on Venus, its surface is perpetually hidden below thick clouds. Only in the last few decades have planetary scientists discovered that Venus is a hot desert world of volcanoes, lava flows, and impact craters that lie at the bottom of a deep, hot atmosphere that is much more dense than Earth's—no spacesuit would allow you to visit this planet's surface. Although its orbit is almost circular, interestingly Venus rotates backward, a fact discovered within the last 60 years. Its slow retrograde rotation results in a solar day that is 116.75 Earth days long—with, of course, the Sun rising in the west and setting in the east. Consult **Celestial Profiles** in Appendix C for a more detailed comparison of Earth's and Venus's data.

runaway greenhouse effect
A greenhouse effect so dramatic that it amplifies itself, becoming stronger with time.

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The Atmosphere of Venus

In composition, temperature, and density, the atmosphere of Venus is more Hades than Heaven. The air is unbreathable, very hot, and very dense. Planetary scientists know this because space probes have descended into the atmosphere and in some cases landed on the surface.

In composition, the atmosphere of Venus is roughly 96 percent carbon dioxide. The rest is mostly nitrogen, with some argon, sulphur dioxide, and small amounts of sulphuric acid, hydrochloric acid, and hydrofluoric acid. There is only a tiny amount of water vapour. On the whole, the composition is deadly and most certainly smells bad. Spectra show that the impenetrable clouds that hide the surface are made up of droplets of sulphuric acid and microscopic crystals of sulphur. This unbreathable atmosphere is 92 times denser than Earth's. We breathe air that is 1000 times less dense than water, but on Venus the air is only 10 times less dense than water. If you could survive the unpleasant composition and intense heat, you could strap wings on your arms and fly.

The surface temperature on Venus is 735 K—hot enough to melt lead, which is understandable because the thick atmosphere creates a severe greenhouse effect. Sunlight filters down through the clouds and warms the surface, but infrared radiation cannot escape because the atmosphere is opaque to infrared. It is the overwhelming abundance of carbon dioxide that makes the greenhouse effect on Venus much more severe than on Earth.

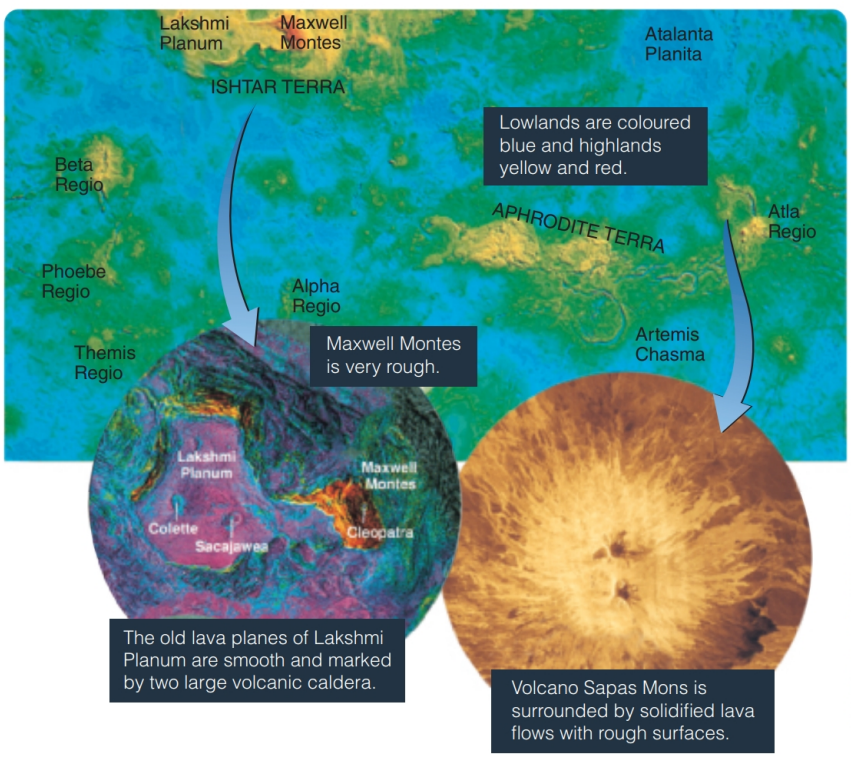
The Surface of Venus

Although the thick clouds and atmosphere on Venus are opaque to visible and infrared light, they are transparent to radio waves. Therefore, orbiting spacecraft have mapped Venus by radar, revealing details as small as 100 m in diameter (Figure 13.8).

Maps of Venus are reproduced using arbitrary colours. For example, lowlands are represented in blue on some maps. However, this is somewhat misleading because there are no oceans on Venus. For other maps the scientists have chosen to give Venus an overall orange tint because sunlight filtering down through the clouds bathes the landscape in a perpetual sunset glow. These maps demonstrate Venus's similarity to Earth in one way, but strangely different in other ways. Nearly 75 percent of Earth is covered by low-lying basaltic sea floors, and 85 percent of Venus is covered by basaltic lowlands. On Venus the lowlands are not sea floors, and the remaining highlands are not the well-defined continents you see on Earth. While Earth is dominated by plate tectonics, something different is happening on Venus.

The northern highland area Ishtar Terra, named Ishtar for the Babylonian goddess of love, is roughly the size of Antarctica (Figure 13.8). At its eastern edge, the mountain called Maxwell Montes thrusts up 12 km (Everest, the tallest mountain on Earth, is 8.8 km high). The mountains bounding Ishtar Terra, including Maxwell, resemble folded mountain ranges, which suggests that some horizontal motion in the crust as well as volcanism has helped form the highlands.

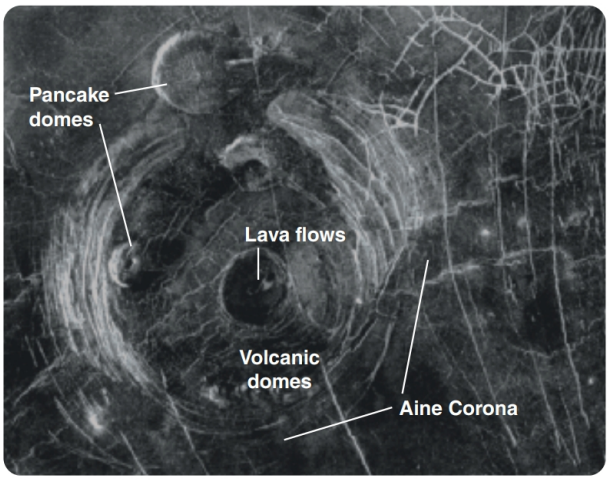
Many features on Venus testify to its volcanic history. Long, narrow lava channels meander for thousands of kilometres. Radar maps reveal many smaller volcanoes,



map: NASA; bottom left: U.S. Geological Survey; bottom right: NASA

Figure 13.8 Notice how three radar maps show different things. The main radar map, made by the Magellan robot probe, shows elevation over most of the surface of Venus, omitting the polar areas. The detailed map of Maxwell Montes and Lakshmi Planum are coloured according to roughness, with orange the roughest terrain. The map of volcano Sapas Mons also shows roughness but is given an orange colour to mimic the colour of sunlight reaching the surface through the thick atmosphere.

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NASA

Figure 13.9 Radar map of surface features on Venus. Aine Corona, about 200 km in diameter, is marked by faults, lava flows, small volcanic domes, and pancake domes of solidified lava.

faults, and sunken regions produced when magma below the surface drained away. However, the random distribution of volcanoes rather than Earth's long volcanic ranges along tectonic plate boundaries definitely point to the lack of tectonic plates on Venus. Other volcanic features include the **coronae**: circular bulges up to 2100 km in diameter bordered by fractures, volcanoes, lava flows, and pancake domes of solidified lava (Figure 13.9). These appear to be produced by rising convection currents of molten magma that push up under the crust. When the magma withdraws, the crust sinks back, and the circular fractures mark the edge of the original upwelling.

Radar images also show that Venus is marked by numerous craters. The number of craters shows that the crust of Venus is younger than the lunar maria but older than most of Earth's active surface. The average age of the surface of Venus is estimated to be roughly half a billion years old. Clearly, geological processes cannot be renewing the surface as rapidly as they do on Earth.

By now you will know that a main geological difference between Venus and Earth is the lack of any plate tectonics on Venus. Whether or not plate tectonics ever played a role in Venus's early geological history remains unknown. However, it seems that at some point in time there were factors that altered Venus's evolutionary path from developing into a habitable world like Earth toward the current Venus with its oppressive atmosphere and searing ground temperatures. Given the recent plethora of exoplanet discoveries we need to understand how Venusian-like planets form and evolve, underscoring the growing interest in exploring Venus more fully.

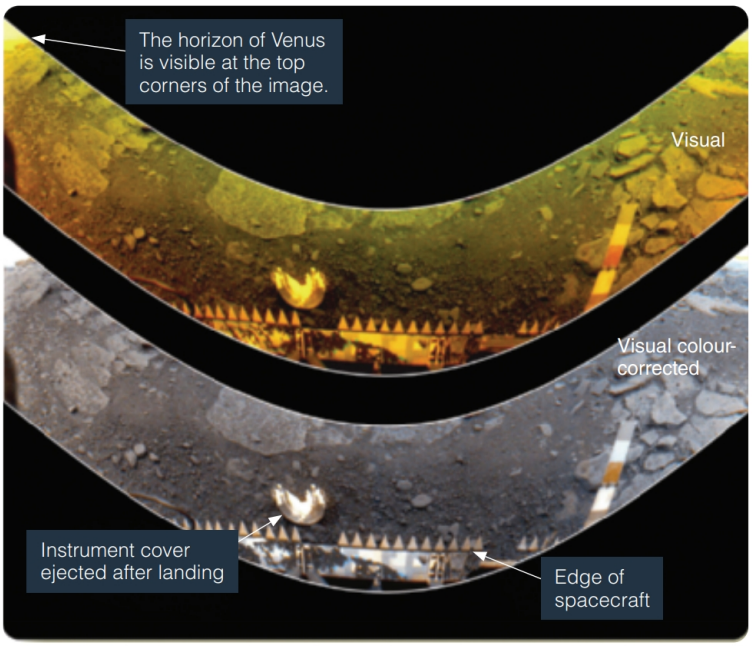
coronae On Venus, the large, round geological faults in the crust caused by the intrusion of magma below the crust.

Both Russian and American robot probes landed successfully on the surface of Venus in the 1970s and 1980s and managed to survive the heat and pressure for a few minutes or hours, transmitting data to Earth. Some of those spacecraft analyzed the rock and snapped a few photographs (Figure 13.10). The surface rocks on Venus are dark grey basalts, much like those in Earth's ocean floors. This evidence confirms that volcanism is important.

The History of Venus

To tell the story of Venus, you must draw together all the evidence and find hypotheses to explain two things: the thick carbon dioxide atmosphere and the peculiar geology.

Calculations show that Venus and Earth have outgassed about the same amount of carbon dioxide, but Earth's oceans have dissolved most of that and converted



NASA

Figure 13.10 The Soviet *Venera 13* lander touched down on Venus in 1982 and carried a camera that swivelled from side to side to photograph the surface. The orange glow in the image is produced by the thick atmosphere; when that glow is corrected digitally, you can see that the rocks are dark grey. Isotopic analysis suggests they are basalts.

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it to sediments such as limestone. If all of the carbon in Earth's sediments and crust were dug up and converted back to carbon dioxide, our atmosphere would be about as dense as the air on Venus, and with similar composition. This suggests that the main difference between Earth and Venus is the lack of water on Venus.

Venus may have had oceans when it was young and much more Earth-like than at present, but being closer to the Sun than Earth it was warmer, and the carbon dioxide in the atmosphere created a greenhouse effect that made the planet even warmer. That process could have dried up any oceans that did exist and prevented Venus from purging its atmosphere of carbon dioxide. In fact, evidence from the composition of Venus's atmosphere indicates that an ocean's worth of water might have been vaporized and lost due to dissociation by ultraviolet light from the Sun. This dissociation of water removed the two hydrogen atoms from the oxygen atom, allowing the lighter hydrogen to escape into space while the slower moving and more massive oxygen atom combined with other atoms. As carbon dioxide continued to be outgassed, the greenhouse effect grew even more severe. Thus, planetary scientists conclude that Venus was trapped in a runaway greenhouse effect.

The intense heat at the surface may have affected the geology of Venus by making the crust drier and more flexible, so it was unable to break into moving plates as on Earth. Although there is no sign of plate tectonics on Venus, there is evidence that convection currents below the crust are deforming the crust to make coronae, push up mountains such as Maxwell, and create some folded mountains like those around Ishtar Terra by minor horizontal crust motions.

As you learned earlier, the small number of craters on the surface of Venus hints that the entire crust has been replaced within the last one-half billion years or so. This may have occurred in a planetwide overturning as the old crust broke up and sank and lava flows created a new crust. Comparisons between Earth and Venus may eventually reveal more about how our own world's volcanism and tectonics work.

Exploration

Both Russian (*Venera*) and American (*Mariner* and *Pioneer*) robot probes landed successfully on the surface of Venus in the 1970s and 1980s and managed to survive the heat and pressure for a few minutes or hours, transmitting data to Earth. Some of those spacecraft analyzed the rock and snapped a few photographs (Figure 13.10). The surface rocks on Venus are dark grey basalts, much like those in Earth's ocean floors, confirming the importance of volcanism. In the early 1990s NASA's *Magellan* orbiting spacecraft measured Venus's surface in unprecedented detail, revealing a relatively young surface covered in lava flows with very few craters (hence the previous comments).

More recently, ESA's *Venus Express* (2004) and Japan's *Akatsuki* (2010) have provided more information about the Venusian atmosphere. At this time there are no other active missions planned.

permafrost Permanently frozen soil.

13.6 Mars

If you ever want to visit another world, Mars may be your best choice. You will need a heated, pressurized spacesuit, but Mars is not as inhospitable as the Moon. It is also more interesting, including the weather, complex geology, craters, volcanoes, and signs that water once flowed over its surface. Mars is about 50 percent farther from the Sun than Earth but its rotational period is very similar to that of Earth, with a solar day of 24.66 hours. As well, its rotational axis is tilted at 25.2° to its orbit; this is similar to that of Earth (23.4°), so there are distinct seasons on Mars. See **Celestial Profiles** in Appendix C for further details on the properties of Mars.

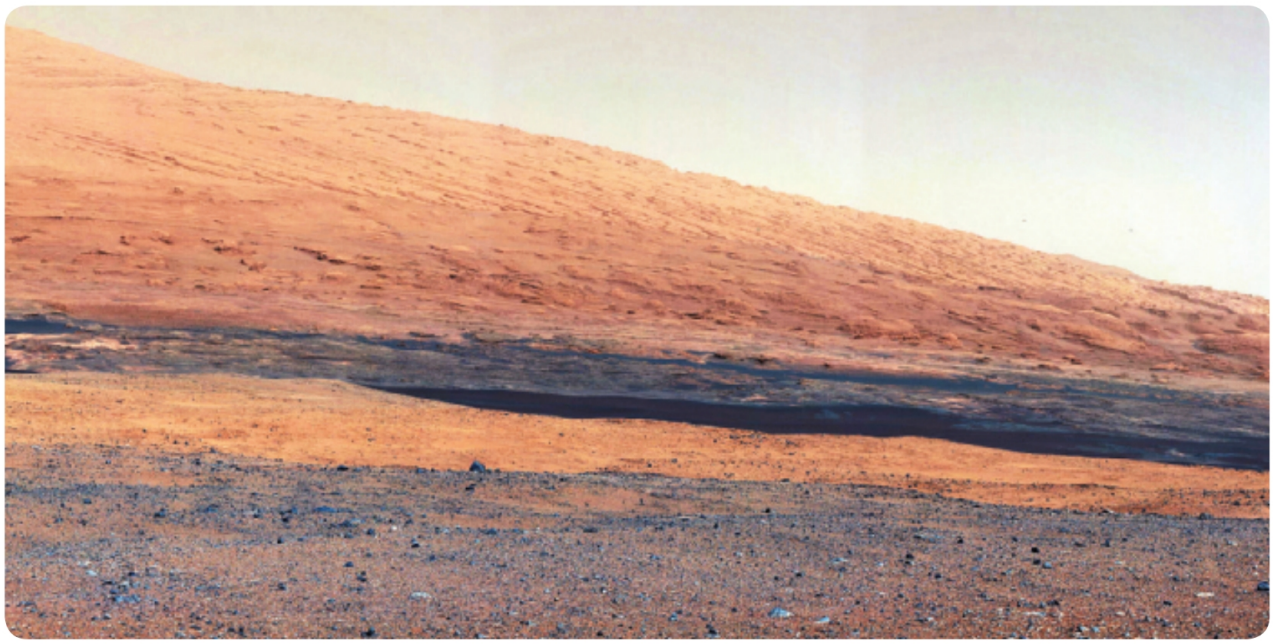
The Atmosphere of Mars

The Martian air contains 95 percent carbon dioxide, 3 percent nitrogen, and 2 percent argon. That is similar to the composition of air on Venus, but the Martian atmosphere is very thin, less than 1 percent as dense as Earth's atmosphere and 1/10 000 as dense as that of Venus.

There is very little water in the Martian atmosphere. Liquid water cannot survive on the surface of Mars because the air pressure is too low: any liquid water would immediately boil away. The polar caps appear to be composed of frozen water ice coated with frozen carbon dioxide (dry ice). Whatever water is present on Mars is frozen either within the polar caps or as **permafrost** in the soil.

Although the present atmosphere of Mars is very thin, there is evidence that the climate once permitted liquid water to flow over the surface, so Mars must have once had a thicker atmosphere. As a Terrestrial planet, it should have outgassed significant amounts of carbon dioxide, nitrogen, and water vapour, but because it was small it could not hold on to its atmosphere. The escape velocity

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NASA

Figure 13.11 This image taken by the Mast Camera on the *Curiosity* rover highlights the interesting geology of Mount Sharp, a mountain inside Gale Crater where the rover landed. Prior to the rover's landing, observations from orbiting satellites indicate that the lower reaches of the mountain are rock layers containing water-bearing minerals.

on Mars is only 5 km/s, less than half of Earth's, so it was easier for rapidly moving gas molecules to escape into space. Furthermore, if Mars had been colder, the gas molecules in its atmosphere would have travelled more slowly and not escaped as easily.

Another process reduced Mars's atmosphere: the lack of an ozone layer to screen out UV radiation. Sunbathing on Mars would be a fatal mistake. Solar UV photons can break atmospheric molecules into smaller fragments. Water, for example, can be broken by UV into hydrogen and oxygen. The hydrogen then escapes into space, and the oxygen easily combines chemically with rocks and soil to form oxides. Iron oxide (rust) in the soil gives Mars its reddish landscape (Figure 13.11). Mars may have had a substantial atmosphere when it was young, but it gradually lost much of that, both by direct escape and by UV destruction. As a result, with a thin atmosphere that does not provide much greenhouse warming nor permit liquid water to persist on the surface, Mars is now a cold, dry world.

Exploring the Surface of Mars

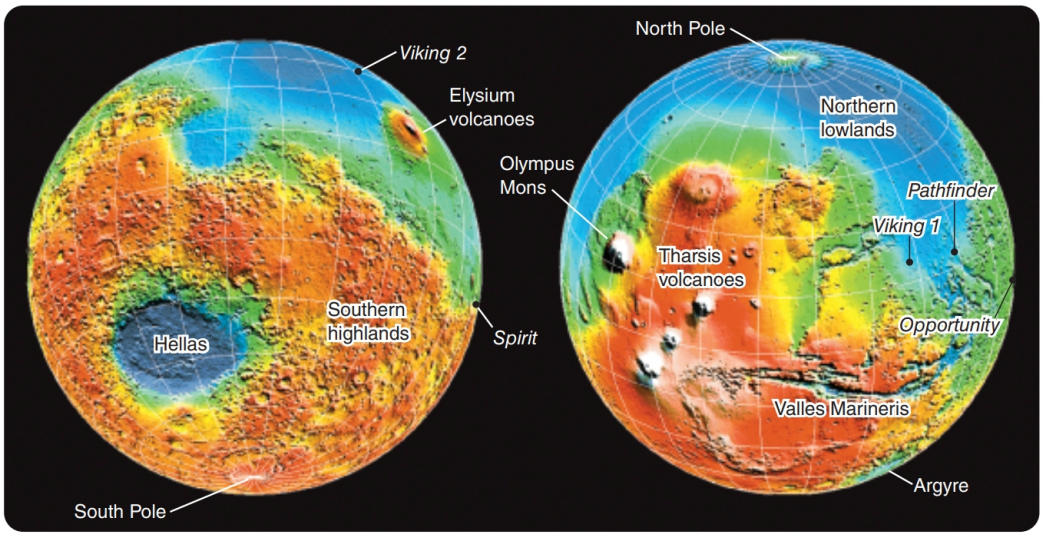
Data recorded by orbiting satellites show that the southern hemisphere of Mars is a heavily cratered highland region up to 4 billion years old. The northern hemisphere is mostly a much younger lowland plain with few craters (see Figure 13.12).

Volcanism is dramatically evident in the Tharsis region of Mars, a highland region of volcanoes and lava flows bulging 10 km above the surrounding surface (see Figure 13.12). A similar uplifted volcanic plain, the Elysium region, is more heavily cratered and eroded and appears to be older than the Tharsis bulge. The lack of impact craters on the slopes of some volcanoes in both Tharsis and Elysium suggests that there has been volcanic activity within the past few hundred million years, and maybe even more recently.

All the volcanoes on Mars are **shield volcanoes**: very broad mountains with gentle slopes that on Earth are produced by hot spots penetrating upward through the crust. Shield volcanoes are not related to plate tectonics; in fact, the large shield volcanoes on Mars, the largest of which is Olympus Mons, provide evidence that plate tectonics has not been significant on that planet. Olympus Mons is 700 km in diameter at its base and rises 25 km high. In comparison, the largest volcano on Earth, also a shield volcano, is Mauna Loa in Hawaii, rising only 10 km above its base on the sea floor (Figure 13.13a). On Earth, volcanoes like those that formed the Hawaiian Islands occur over rising currents of hot material in the mantle. Because the crust plate moves horizontally, a chain of volcanoes is formed instead of a single large feature (Figure 13.13b).

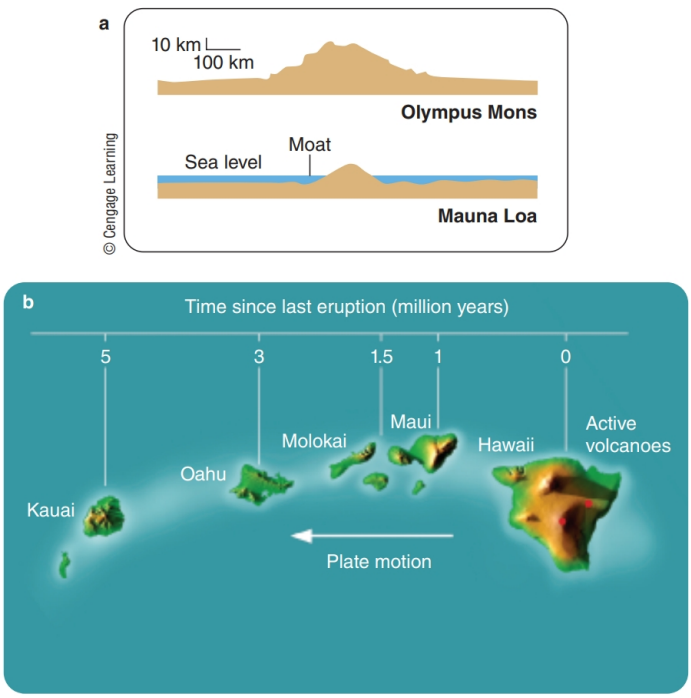
shield volcano Wide, low-profile volcanic cone produced by highly liquid lava.

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NASA

Figure 13.12 These hemisphere maps of Mars are colour-coded to show elevation. The northern lowlands lie about 4 km below the southern highlands. Volcanoes are very high (white), and the giant impact basins, Hellas and Argyre, are low. Note the depth of the great canyon Valles Marineris.



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Figure 13.13 (a) Olympus Mons on Mars is much larger than Mauna Loa, the largest mountain on Earth. Mauna Loa is so heavy that it has sunk into Earth's crust, producing an undersea moat, but Olympus Mons has not, suggesting Mars's crust is much stronger than Earth's. (b) Volcanoes such as Mauna Loa do not grow very large on Earth because the crust plates move horizontally and carry older volcanoes away from hot spots.

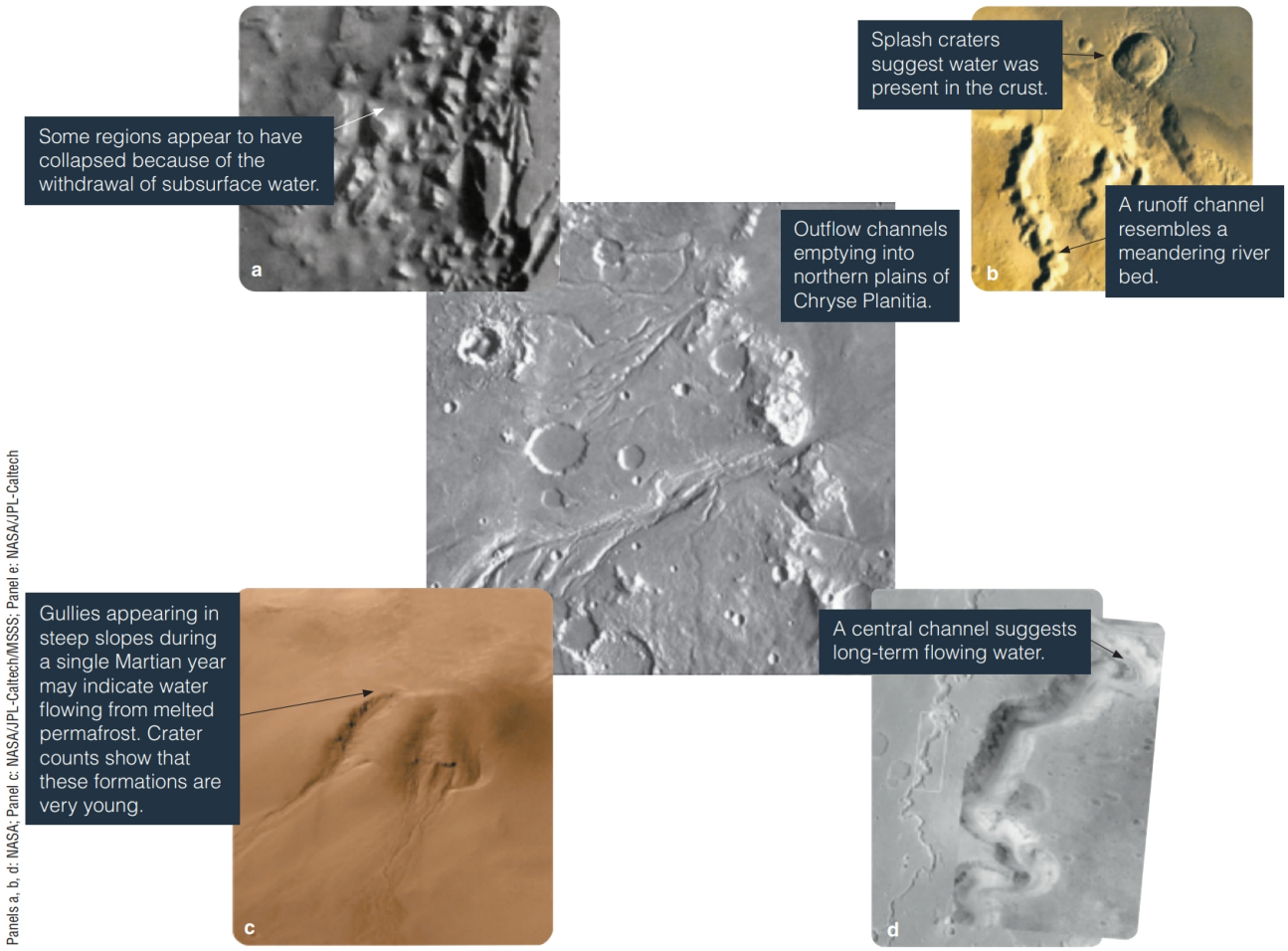
A lack of plate motion on Mars has allowed rising currents of magma to heat the crust repeatedly in the same places and build Olympus Mons as well as other very large volcanic shields, especially in the Tharsis region (Figure 13.12).

When the crust of a planet is strained, it may break, producing faults and rift valleys. Near the Tharsis region is a great valley, Valles Marineris, named after the *Mariner 9* spacecraft that first photographed it (see Figure 13.12). The valley is a block of crust that has dropped downward along parallel faults. Erosion and landslides have further modified the valley into a great canyon. It is four times deeper, nearly 10 times wider, and over 10 times longer than the Grand Canyon. To put this into perspective, Valles Marineris is about as long as the distance from Calgary to Halifax and twice as wide as Vancouver Island in many spots. The number of craters in the valley indicates that it is 1 to 2 billion years old, placing its origin sometime before the end of the most active volcanism in the Tharsis region.

Searching for Water on Mars

It is well known that water in its liquid state has been crucial to the evolution of life on Earth and similarly to the development of life on any other galactic object. Consequently, astronomers define the habitable zone around any star as the location where water in its liquid state can exist. This explains the enthusiasm that humanity has had with the search for water on Mars, especially given the earlier views of Percival Lowell and others on the existence of genuine Martian life. As you learned earlier, liquid water cannot exist on the surface of Mars now because of its low atmospheric pressure and low surface temperature. But was this always the case? Could

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Panels a, b, d: NASA; Panel c: NASA/JPL-Caltech/MSSS; Panel e: NASA/JPL-Caltech

Figure 13.14 These visual-wavelength images made by the *Viking* orbiters and *Mars Global Surveyor* show some of the features that suggest liquid water on Mars. Outflow channels and runoff channels are old, but some gullies may be quite recent.

water have been abundant on Mars at some time in the past, and could conditions under which life started on Earth have also existed on Mars around the same time? It is this logical reasoning and questioning that drives astronomers to find ways to explore Mars in an attempt to solve this mystery.

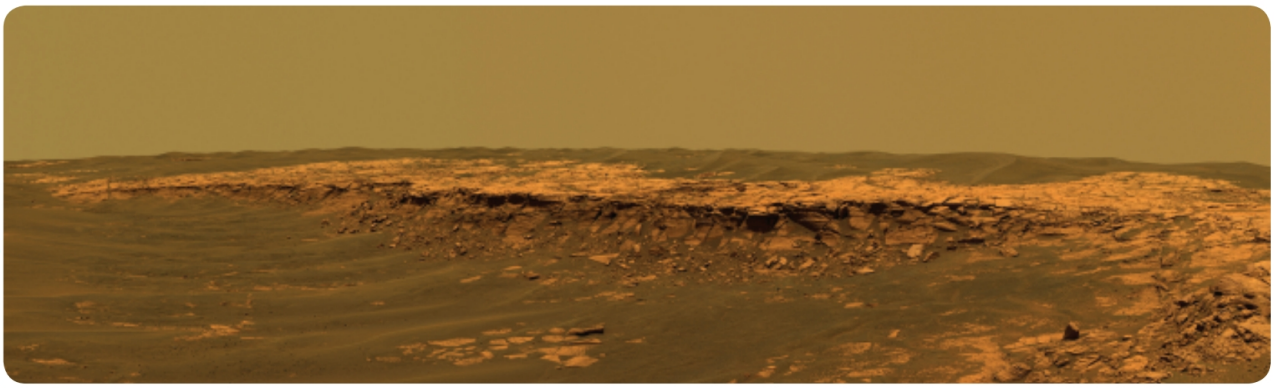
In the mid-1970s NASA's *Viking* orbiters provided early photographic evidence hinting that water flowed abundantly early in Mars's history. These photos revealed two kinds of water-related features. **Outflow channels** appear to have been cut by massive floods carrying as much as 10 000 times the water flowing down the St. Lawrence River. In a matter of hours or days, such floods swept away geological features and left scarred land such as that shown in the following images made by *Viking* orbiters and the *Mars Global Surveyor*. In contrast, **valley networks** look like meandering riverbeds with sandbars, deltas, and tributaries typical of streams that flowed for extended periods of time (Figure 13.14). The number of craters on top of these features reveals that they are quite old. It is now widely accepted that Mars's surface was covered with significant amounts of water early in its history, but these large bodies of water disappeared long ago.

Interestingly, recent observations by the orbiters *Mars Reconnaissance Orbiter* (2006) and *Mars Odyssey* (2001) show that small amounts of liquid water may still exist

outflow channel Geological features on Mars and Earth caused by flows of vast amounts of water released suddenly.

valley network A system of dry drainage channels on Mars that resembles the beds of rivers and tributary streams on Earth.

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Figure 13.15 Mars is a red desert planet, as shown in this true-colour photograph by the rover *Opportunity*. The rock outcrop is a metre-high crater wall. Dust suspended in the atmosphere colours the sky red-orange. Data from orbiters, landers, and rovers show that billions of years ago Mars was less of a desert and had water on its surface.

underground, occasionally seeping into gully deposits not observed previously. Not all scientists attribute the gully formation, which often appears to be seasonal, to liquid water or brine. Some suggest that conditions favour dry grains lubricated by liquid carbon dioxide, and this conclusion is supported by recent (2017) spectrographic data from *Mars Odyssey*. In any event, there is insufficient liquid of any source to develop life as we know it.

All water on Mars now exists as ice, and most of it is contained in caps covering both north and south Martian poles. At the south pole the water ice is covered permanently by a thick carbon dioxide layer. It is estimated that there is enough water ice in the south cap to cover the entire planet to a depth of at least 10 m if melted. However, there is also water ice just below the Martian surface as discovered by orbiters, landers, and rovers.

Spacecraft in orbit around Mars using remote instruments have detected large amounts of water frozen in the soil. Images made from orbit also show regions of jumbled terrain and gullies leading down slopes, suggesting water has flowed onto the surface from underground sources, perhaps melting of subsurface ice. The terrain at the edges of the northern lowlands has been compared to shorelines, and some scientists suspect that the northern lowlands were filled with an ocean roughly 3 billion years ago. Look again at Figure 13.12, where the lowlands have been colour-coded blue, and notice the major outflow channels leading from highlands into lowlands, like rivers flowing into an ocean.

In 2004, NASA successfully landed two rovers named *Spirit* and *Opportunity* relatively close to the Martian equator. Both rovers landed in areas suspected of having had water on their surfaces, and both made exciting discoveries. Using close-up cameras, the rovers found small spherical concretions of the mineral hematite (dubbed "blueberries") that must have formed in water (Figure 13.15). In other places, they found layers of sediments with ripple marks and crossed layers showing deposits that must have formed in moving water. You can see both of these features in Figure 13.16. Chemical analysis revealed minerals in the soil, such as sulphates, that are left behind when standing water evaporates.

In 2008, the space probe *Phoenix* landed in the north polar region of Mars and used its robotic arm to uncover

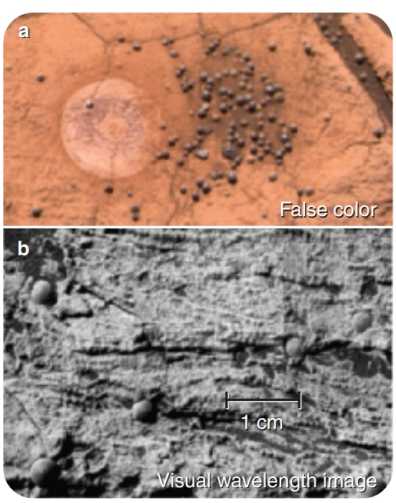


Figure 13.16 (a) Rover *Opportunity* photographed hematite concretions ("blueberries") weathered from rock. The round mark is a spot cleaned by the rover. The spheres appear to have grown as minerals collected around small crystals in the presence of water. Similar concretions are found on Earth. (b) The layers in this rock were deposited as sand and silt in rapidly flowing water. From the way the layers curve and cross each other, geologists can estimate that the water was at least 10 centimetres deep. A few "blueberries" are also visible in this image.

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water ice frozen in the Martian soil. Detailed chemical analyses of soil samples were completed confirming the presence of water and minerals necessary for any life that might exist there.

Finally, in August 2012, NASA's Mars Science Laboratory mission successfully landed the largest rover to date, *Curiosity*, in the Gale Crater, a site near the Martian equator. This huge 150-km-wide crater is highlighted by Aeolis Mons, a mountain that rises to 5.5 km at its peak. This landing site was chosen because it appeared to harbour many signs that water was present sometime in its history. Early in its wanderings *Curiosity* found clear evidence of a watery past by finding rounded rocks that must have been shaped by tumbling in rapid waterways. Other evidence points to a wetter and warmer past in this part of the Martian landscape.

Mars has water, but it is hidden. When humans reach Mars, they will not need to dig far to find water ice. Using solar power to break the water into hydrogen for use as fuel, and oxygen for breathing, the water ice is buried treasure. Although it is now a desert world, someday an astronaut may scramble down an ancient Martian stream bed, turn over a rock, and find a fossil. Life, if it ever existed on Mars, may have hung on by retreating to warm and wet oases underground. You will learn in the final chapter about possible evidence of ancient life in one of the Martian meteorites.

A History of Mars

Did Mars ever have plate tectonics? Where did the water go? These fundamental questions challenge you to assemble the evidence and hypotheses for Mars and tell the story of its evolution. (See **How Do We Know? 13.2**.)

The history of Mars, like that of Venus, has been dominated by volcanism, but the differences are striking. Read **Visualizing Astronomy 13.2, When Good Planets Go Bad**, and notice four important points:

HOW DO WE KNOW? 13.2



The Present Is the Key to the Past

How can we know what happened long ago if there weren't any witnesses? Geologists are fond of saying, "The present is the key to the past." They mean that you can learn about the history of Earth by looking at the present condition of Earth's surface. The position and composition of various rock layers in the Grand Canyon, for example, tell you that the western United States was once at the floor of an ocean. This principle of geology is still relevant for understanding the history of other planets such as Venus and Mars.

In the late 1700s, naturalists first recognized that the present gave them clues to the history of Earth. At the time, that was astonishing because most people assumed that Earth had no history. That is, they assumed either that Earth had been created in its present state as described in the Old Testament or that Earth was eternal. In either case, people commonly assumed that the hills and mountains they saw around them had always existed, more or less as they were. By the 1700s, naturalists began to see evidence that the hills and mountains were not eternal but were the result of past processes and were slowly changing. That gave rise to the idea that Earth had a history.

As those naturalists made the first attempts to thoughtfully and logically explain the nature of Earth by looking at the evidence, they were inventing modern geology as a way of understanding Earth. What Copernicus, Kepler, and Newton did for the heavens in the 1500s and 1600s, the first geologists did for Earth beginning in the 1700s. Of course, the invention of geology as the study of Earth led directly to the modern attempts to understand the geology of other worlds.

Geologists and astronomers share a common goal: to reconstruct the past from the evidence. Whether you study Earth, Venus, or Mars, you are looking at the present evidence and trying to reconstruct the past history of the planet by drawing on observations and logic to test each step in the story. How did Venus get to be covered with lava, and how did Mars lose its atmosphere? The final goal of planetary astronomy is to draw together all the available evidence (the present) to tell the story (the past) of how the planet got to be the way it is. Those first geologists in the 1700s would be fascinated by the stories planetary astronomers tell today.

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Visualizing Astronomy 13.2

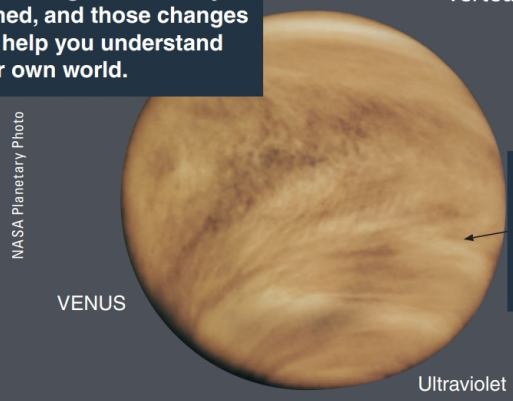
WHEN GOOD PLANETS GO BAD

1 VENUS: RUNAWAY GREENHOUSE

Venus and Mars haven't really gone wrong, but they have changed since they formed, and those changes can help you understand your own world.

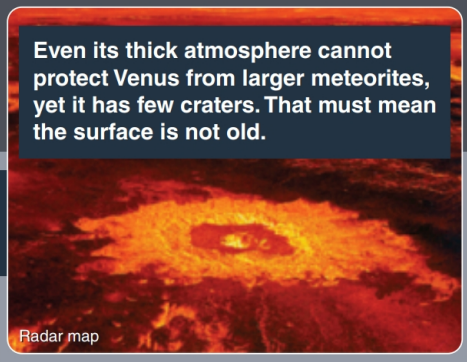
Venus and Earth have outgassed about the same amount of CO_2, but Earth's oceans have dissolved most of Earth's CO_2 and converted it to sediments such as limestone. If all of Earth's sedimentary carbon were dug up and converted back to CO_2, our atmosphere would be much like Venus's.

Because Venus was warmer when it formed, it had little if any liquid water to dissolve CO_2, and that produced a greenhouse effect that made the planet even warmer. The planet could not purge its atmosphere of CO_2, and as more was outgassed, Venus was trapped in a runaway greenhouse effect.



Only 0.7 AU from the Sun, Venus receives almost twice the solar energy per square metre that Earth does. Moved to Venus's orbit, Earth's surface would be 50°C hotter.

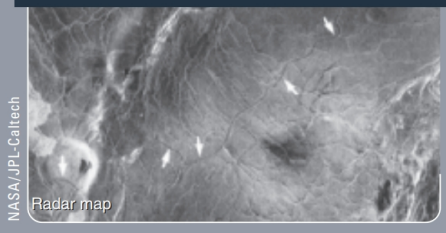
Even its thick atmosphere cannot protect Venus from larger meteorites, yet it has few craters. That must mean the surface is not old.

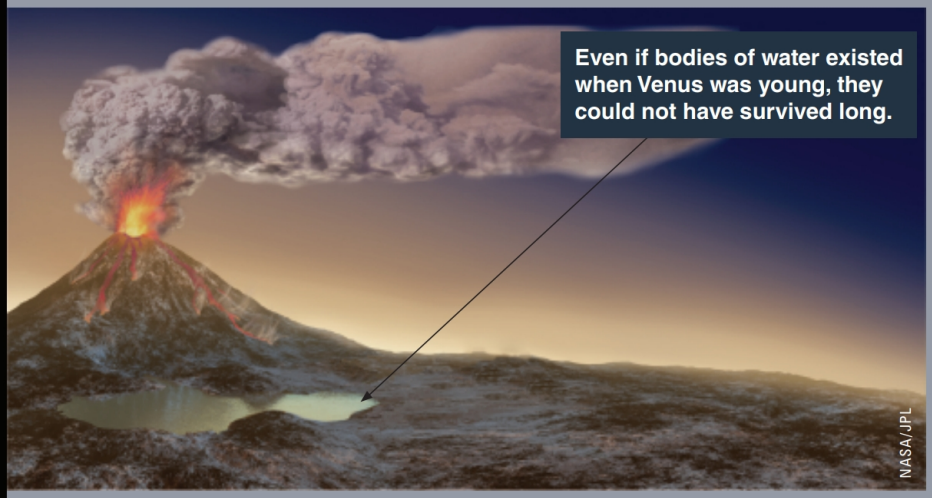


2

Lava covers Venus in layers of basalt, and volcanoes are common. Some of those volcanoes may be active right now, whereas others are dormant. Traces of past lava flows show up in radar images including long narrow valleys cut by moving lava.

Baltis Vallis (arrows), at least 6800 km long, is the longest lava flow channel in the solar system.





Even if bodies of water existed when Venus was young, they could not have survived long.

2a

The crust of Venus must be no older than 0.5 billion years. One hypothesis is that an earlier crust broke up and sank in a sea of magma as fresh lava flows formed a new crust. Such resurfacing events might occur periodically on a hot, volcanic planet like Venus.

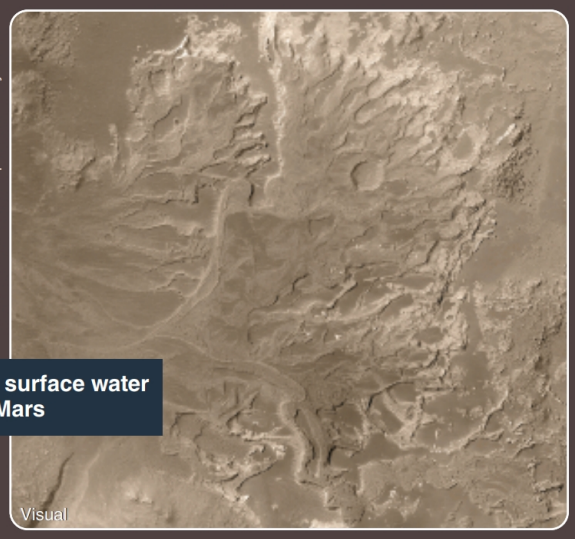
What could cause a resurfacing event? Models of the climate on Venus show that an outburst of volcanism could increase the greenhouse effect and drive the surface temperature up by as much as 100°C. This could soften the crust, increase the volcanism, and push the planet into a resurfacing episode. This type of catastrophe may happen periodically on Venus, or the planet may have had just one resurfacing event about half a billion years ago.

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MARS: RUNAWAY REFRIGERATOR

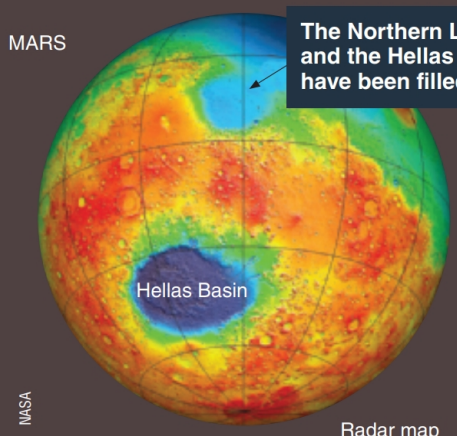
3 When Mars was young, water was abundant enough to flow over the surface in streams and floods, and may have filled oceans. That age of liquid surface water ended more than 3 billion years ago. The climate on Mars has changed as atmospheric gases and water were lost to space and as water was frozen into the soil as permafrost.



NASA/JPL-Caltech/Malin Space Science Systems

Visual

Evidence of surface water erosion on Mars



NASA

Radar map

The Northern Lowlands of Mars and the Hellas Basin may once have been filled with water.

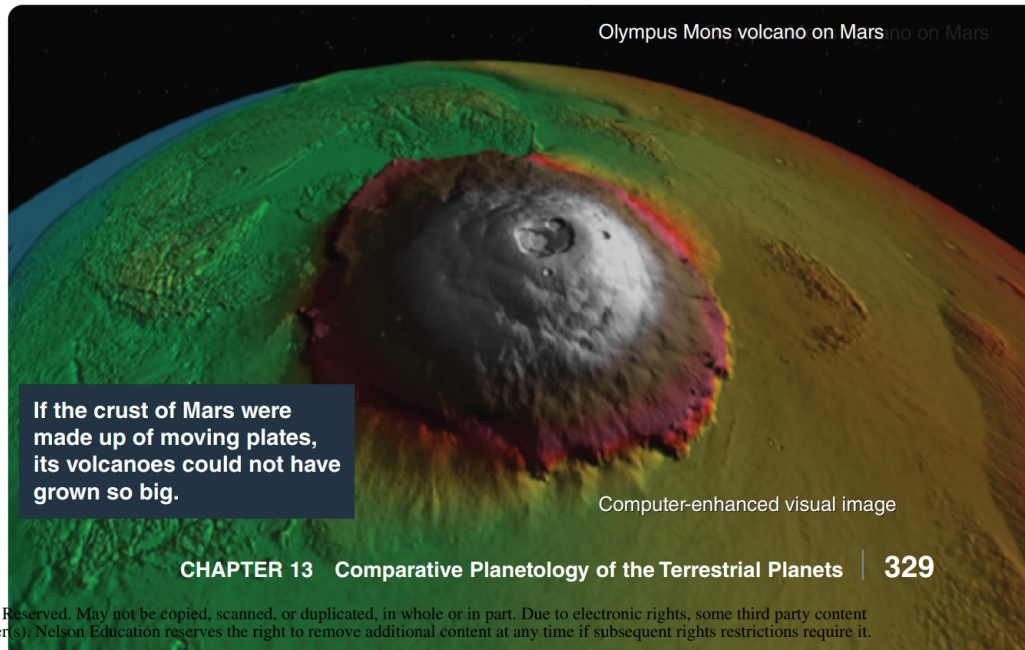
3a This distributary fan formed where an ancient stream flowed into a lake within a crater. Sediment deposited in the still lake water formed a lobed delta that later became sedimentary rock. Detailed analysis reveals that the stream changed course repeatedly, showing that the stream was not just a short-term flood.

Early in the history of Mars when its crust was thin, convection in the mantle could have pushed up volcanic regions such as Tharsis and Elysium, and limited plate motion could have produced Valles Marineris, but Mars cooled too fast, and its crust never broke into moving tectonic plates as did Earth's crust.

4

As its crust thickened, volcanism abated, and Mars lost the ability to replenish its waning atmosphere.

4a Mars has very large volcanoes, and their size shows that the crust has grown thick as the little planet has lost its heat to space. A thinner crust could not support such large volcanoes.



Olympus Mons volcano on Mars

NASA GSFC Scientific Visualization Studio

If the crust of Mars were made up of moving plates, its volcanoes could not have grown so big.

Computer-enhanced visual image

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1. The difference between Venus and Earth is not in the amount of CO_2 they have outgassed but in the amount they have removed from their atmospheres. Being warmer and consequently having less liquid water on its surface sealed Venus's fate in having a runaway greenhouse effect.
2. Venus is highly volcanic, with a crust made up of lava flows that have covered over any older crust.
3. Mars is significantly smaller than Earth, with gravity too weak to prevent much of its atmosphere from leaking away. There is strong evidence of past water, but whatever is left is frozen in the soil or polar caps.
4. Mars is small and cooled quickly. Its crust has grown thick, and volcanism has dropped to such a low level that it cannot replenish the gases lost to space.

The history of Mars is a case of arrested development. The planet began by differentiating into a crust, mantle, and core. Measurements from orbiting spacecraft reveal that it has a dense core but no planetwide magnetic field. The core must have cooled quickly and shut off the dynamo effect that would have produced a field.

The crust of Mars is now quite thick, as shown by the mass of the Olympus Mons volcano (refer to Figure 13.13), but it was probably thinner in the past. Cratering may have broken or at least weakened the crust, triggering lava flows that flooded some basins. Mantle convection may have pushed up the Tharsis and Elysium volcanic regions and broken the crust to form Valles Marineris, but moving crustal plates never dominated Mars. There are no folded mountain ranges on Mars and no sign of plate boundaries. As the planet cooled, its crust grew thick and immobile.

For Mars, the last stage of planetary development has been one of slow decline. Volcanoes may still occasionally erupt, but the little planet has lost much of its internal heat, and most volcanism occurred long ago. At some point in the history of Mars, water was abundant enough to flow over the surface in great floods and may have filled an ocean, but the age of liquid water must have ended more than 3 billion years ago. The climate on Mars changed as the atmosphere gradually became thinner. Atmospheric gases and water were lost to space, and the volcanic activity that could have replaced them has nearly stopped.

Exploration

Fascination with Mars has led to it being the most explored planet in the solar system. Four countries have launched over 50 missions to Mars since the early 1960s, although interplanetary robotic exploration has proven to be challenging—leading to a high failure rate, particularly in the early years.

The first successful flyby was NASA's *Mariner 4* (1964), while the Soviet *Mars 2* (1971) was the first spacecraft to orbit Mars. Four years later NASA successfully placed a robotic lander on Mars (from orbiting *Viking 2*) that returned data for 1281 sols (Martian days). However, it would take another 20 years before a rover (*Sojourner*), launched from the USA's *Mars Pathfinder*, scampered around the Martian surface for 83 sols transmitting pictures of the local landscape. Recently, both India (*Mars Orbiter Mission*, affectionally known as MOM) and the ESA (*Mars Express*) have successfully placed working orbiters around Mars.

The missions that have, perhaps, garnered the most public interest have been NASA's twin rovers *Spirit* and *Opportunity*, which travelled from their respective landing sites on opposite sides of the planet to explore Martian climate and geology. *Opportunity*, nicknamed "Oppy," operated from 2004 until 2018 (55 times longer than its planned mission period), having travelled just over 45 km during its lifetime. One of the rovers' most important findings has been clear evidence that liquid water once existed at both landing sites. Currently, a car-sized rover, *Curiosity*, is exploring the Gale Crater near the Martian equator, drilling into rocks and examining the resulting rock powder using spectral and chemical analysis, among other activities. As of the time of writing *Curiosity* remains operational (see Figure 13.17). Most recently (late 2018), NASA has successfully landed the rover *InSight* at Elysium Planitia to study the deep interior of Mars.

Future missions include a joint Russia/ESA rover (*Rosalind Franklin*) to study the possible existence of microscopic life, NASA's *Mars 2020* rover focusing on astrobiology, a Chinese *2020 Mars Mission* utilizing both a lander and a small rover, and UAE's *Hope Mars Mission* that intends to examine the Martian climate. Evidently, Mars continues to be of great interest to all humanity.

The Moons of Mars

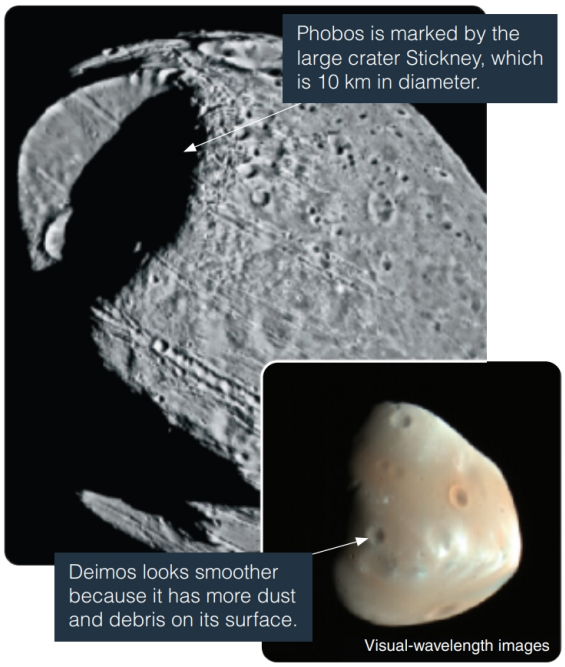
Unlike Mercury or Venus, Mars has moons. Small and irregular in shape, Phobos (28 × 23 × 20 km in diameter) and Deimos (16 × 12 × 10 km) are almost certainly captured asteroids (see Figure 13.18). These moons are so small they cannot pull themselves into spherical shape. Phobos and Deimos are not just small; they are tiny. And an athletic astronaut who could jump 2 m high

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top image: NASA/JPL-Caltech/Malin Space Science Systems; bottom image: NASA/JPL-Caltech/MSSS

Figure 13.17 (a) A *Curiosity* self-portrait taken at the spot in Gale Crater where the first scoop sampling was taken. (b) The scoop mark showing the patch of dust and sand taken on October 7, 2012.



Damon Simonelli and Joseph Ververka, Cornell University/NASA; Deimos: NASA; NASA

Figure 13.18 The moons of Mars are too small to pull themselves into spherical shape. The two moons, shown here to scale, were named for the mythical attendants of the god of war, Mars. Phobos was the god of fear, and Deimos was the god of dread.

on Earth could jump almost 3 km on Phobos. However they formed, these moons are so small that any interior heat would have leaked away very quickly, and there is no evidence of any internally driven geologic activity on either object.

Some futurists suggest that the first human missions to Mars may not land on the planet's surface but instead could build a colony on Phobos or Deimos. These plans involve speculation that these moons and other asteroids may have water in deep interior rocks that colonists could use.

The **Big Picture**

What Are We? Comfortable But Curious

Humans have intense curiosity about their world. We want to know how things work, we want to know what happened in the past, and we want to know what the future might be like. We have a longing to explore other worlds, but leaving Earth is difficult for two reasons. First, to achieve escape velocity you need a powerful, expensive rocket. Second, we face evolutionary challenges. If you leave Earth, you have to take the Earthly environment with you.

On the Moon, astronauts' spacesuits provided them with air to breathe, water to drink, and climate control. Their

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spacesuits could not provide artificial gravity, and medical tests show that low-gravity conditions cause serious deterioration of bones and muscles unless difficult preventive measures are taken. It would be hard to stay healthy away from Earth for long periods of time. The Terrestrial planets and moons are the only ones in our solar system that you might reasonably expect to visit, and few are welcoming. Visiting Venus would require a deep-sea submersible. To explore Mercury you would need a superpower cooling system. Mars, the friendliest, is only somewhat more hospitable than the Moon. Even Titan, the moon that seems to have some Earth-like characteristics, would be a very hostile place to explore.

Many planets in the universe probably look like the Moon and Mercury—small, airless, and cratered. Some are made of stone, others are made mostly of ices because they formed farther from their star, and many others are more like our Jovian planets. If you randomly visited a Terrestrial planet anywhere in the universe, you would probably stand on a moonscape.

Earth is unique in our solar system but probably not rare within our galaxy. The Milky Way Galaxy contains more than 100 billion stars, and more than 100 billion galaxies are visible throughout the universe with existing telescopes. Most of those stars probably have planets, and although many planets may look like our Moon or Mercury, there must be plenty of Earth-like worlds.

As you look around where you live you can feel comfortable living on such a beautiful planet, but this was not always the case. The craters on the Moon and the rocks returned by astronauts show that the Moon formed with a sea of magma. Mercury seems to have had a similar history, so Earth may have formed the same way. Its surface was once a seething ocean of liquid rock swathed in a hot, thick atmosphere, torn by eruptions of more rock, explosions of gas from the interior, and occasional impacts from space. The Moon and Mercury assure you that Terrestrial planets began in this way. Earth has evolved to become your home world, but never forget that Mother Earth has had a violent past.

Review and Discussion Questions

Review Questions

1. Why would you include the Moon in a comparison of the Terrestrial planets?
2. In what ways is Earth unique among the Terrestrial planets?
3. How do you know that Earth differentiated?
4. How are earthquakes in Hawaii different from those in southern California?
5. What characteristics must Earth's core have in order to generate a magnetic field?
6. How do island chains located in the centres of tectonic plates such as the Hawaiian Islands help you understand plate tectonics?
7. What has produced the oxygen in Earth's atmosphere?
8. How does the increasing abundance of CO_2 in Earth's atmosphere cause a rise in Earth's temperature?
9. Why would a decrease in the density of the ozone layer cause public health problems?
10. Why doesn't Earth have as many craters as the Moon?
11. Discuss the evidence and hypotheses concerning the origin of Earth's moon.
12. What evidence indicates that plate tectonics does not occur on Venus? On Mars?
13. What evidence suggests that Venus has been resurfaced within the last half billion years?
14. Why are the atmospheres of Venus and Mars mostly carbon dioxide? Why is the atmosphere of Venus very dense, but the atmosphere of Mars is very thin?
15. Why did Venus suffer from the runaway greenhouse effect, but Earth has avoided it so far?
16. What evidence indicates that there has been liquid water on Mars?
17. Why do astronomers conclude that the crust on Mars must be thicker than Earth's crust?
18. **How Do We Know?** Why is heat flow the key to understanding a planet's surface activity?
19. **How Do We Know?** How is solving a crime that had no witnesses similar to figuring out what happened to Venus and Mars's oceans?

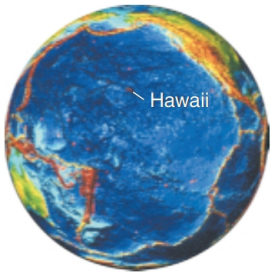
Discussion Questions

1. If you orbited a planet in another solar system and discovered oxygen in its atmosphere, what might you expect to find on its surface?
2. If liquid water is rare on the surface of planets, most Terrestrial planets must have CO_2-rich atmospheres. Why?
3. If you visited a planet in another solar system and discovered that it was heavily cratered, but its small moon was nearly crater free, why would that be a surprise? Speculate about what might have happened to those objects.

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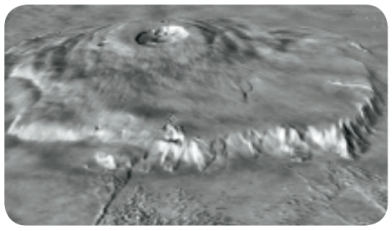
Learning to Look

1. Look at the following globe of Earth, and look for volcanoes scattered over the Pacific Ocean. What is producing these volcanoes?



National Geographical Data Center

2. Olympus Mons on Mars is a very large volcano. In this image you can see multiple calderas superimposed at the top. What do those multiple calderas and the immense size of Olympus Mons indicate about the geology of Mars?


NASA

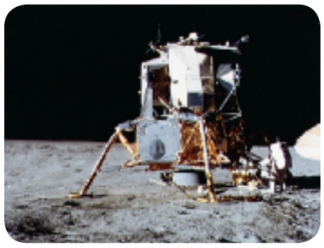
3. In what ways is the photo below a typical view of the surface of planet Earth? How is it unusual among planets in general?


William K. Hartmann/Planetary Science Institute

4. What do you see in the photo below that suggests heat is flowing out of Earth's interior?


USGS

5. In the photo below, Astronaut Alan Bean works at the *Apollo 12* lander *Intrepid*. Describe the surface you see. What kind of terrain did they land on—for this, the second human landing on the Moon?


NASA

STUDY TOOLS

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PART FOUR

14 The Outer Solar System

CHAPTER OUTLINE

14.1 Exploring the Outer Planets
14.2 Jupiter
14.3 Saturn
14.4 Uranus and Neptune: Ice Giants
14.5 Dwarf Planets

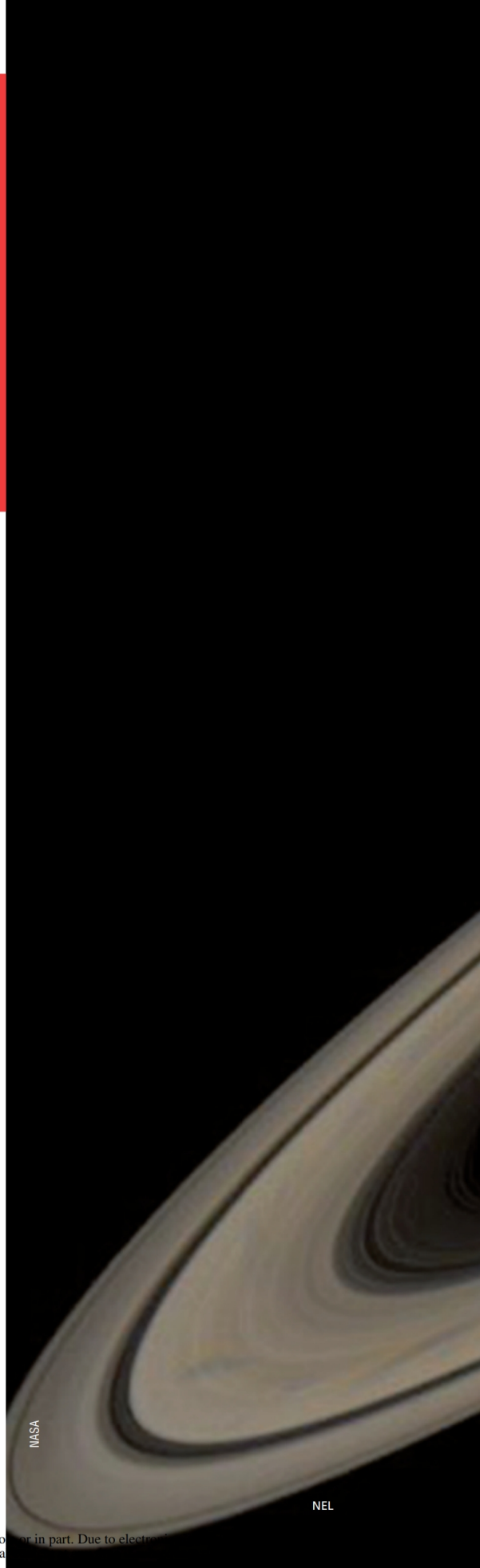
GUIDEPOST

In the previous chapter, you studied how Earth and the other Terrestrial planets evolved to their present forms. In this chapter, the Jovian (Jupiter-like) planets will challenge your imagination. They are such alien worlds that they would be unbelievable if we didn't have direct observational evidence to tell us what they are like. In contrast, Pluto and the other bodies in the Kuiper belt are not planets but intriguing clues about the planet-forming process.

As you explore, you will find answers to four important questions:

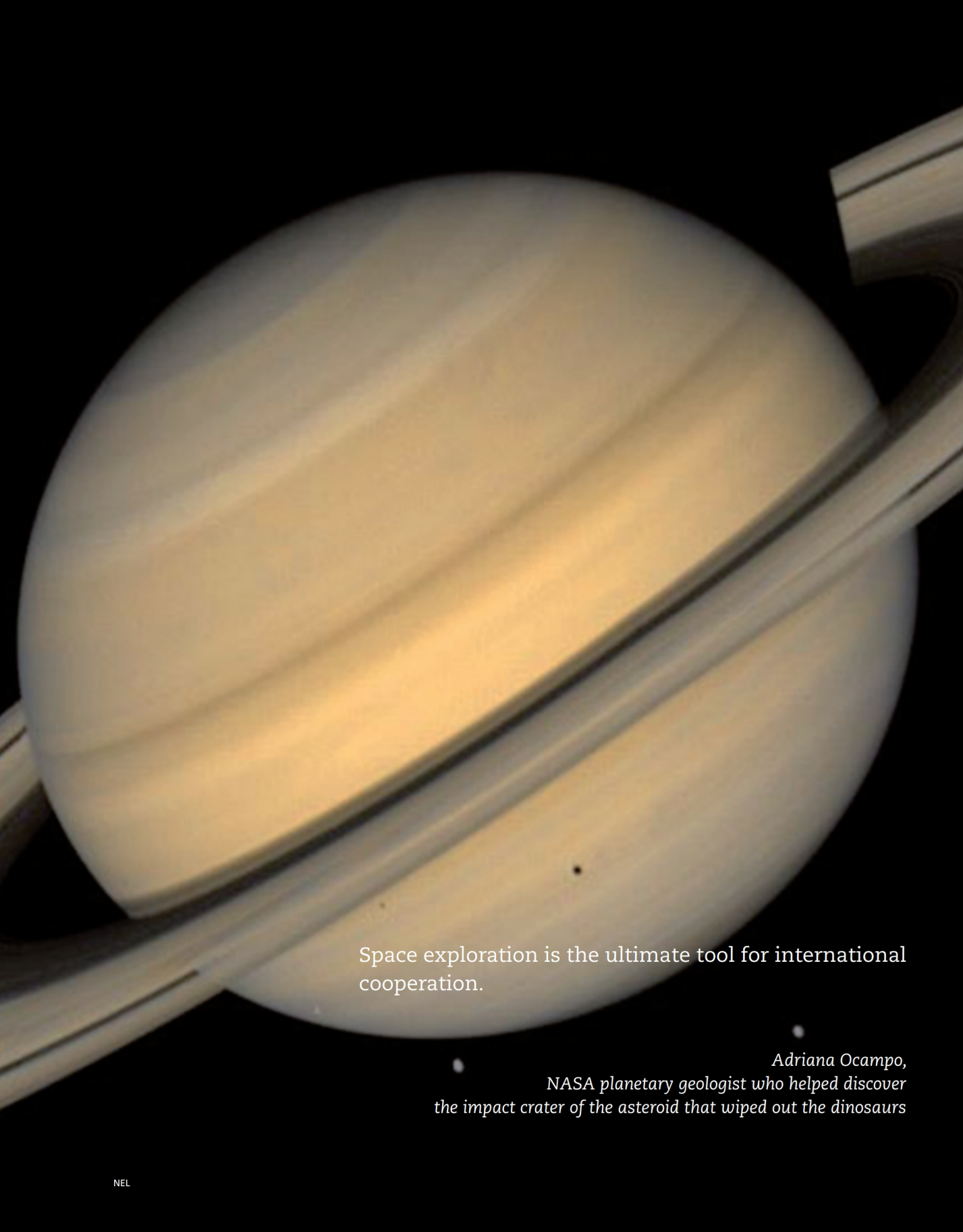
- What are the properties of the Jovian planets?
- What is the evidence that some moons in the outer solar system have been geologically active?
- How are planetary rings formed and maintained?
- What do Pluto and the other Kuiper belt objects tell us about the formation of the solar system?

In Chapter 13 and also in this chapter you learn about the individual planets and see some patterns emerge. In Chapter 12 you learned about a comprehensive theory for the formation of the solar system. That theory explains the overall characteristics of the planets as well as the meteoroids, asteroids, and comets that also orbit the Sun, and it predicts that planetary systems should be common around other stars. In fact, you learned that astronomers have found hundreds of such systems.



NASA

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Space exploration is the ultimate tool for international cooperation.

Adriana Ocampo,
NASA planetary geologist who helped discover
the impact crater of the asteroid that wiped out the dinosaurs

The worlds of the outer solar system can be studied from Earth, but much of what astronomers know has been radioed back to Earth from space probes. The *Pioneer* and *Voyager* probes flew past the outer planets in the 1970s and 1980s, the *Galileo* probe orbited Jupiter in the late 1990s, and the *Cassini* orbiter and *Huygens* probe arrived at Saturn in 2004. The *New Horizons* probe flew past Pluto in 2015 and has now sailed deeper into the Kuiper belt. This chapter includes images and data returned by these robotic explorers.

14.1 Exploring the Outer Planets

By now you will know that the outer planets in our solar system include Jupiter, Saturn, Uranus, and Neptune, in that order as you move outward from the asteroid belt. They are normally referred to as Jovian planets as they are all similar to Jupiter (named after a Roman god known as Jove). Each of these outer worlds is, in many ways, the antithesis of Earth. The terrestrial planets you studied in the previous chapter have small or non-existent atmospheres surrounding large, solid or liquid rocky cores. The Jovian planets, on the other hand, have traditionally been viewed as bodies with extensive, thick atmospheres surrounding a relatively small, solid core, although whether these four giant planets have solid cores should be treated with a healthy dose of skepticism as we really do not know their exact composition. Recent data from *Juno*, the latest orbiter mission to Jupiter, have indicated that the core is likely not solid but rather a loose collection of metallic compounds.

Figure 14.1 compares these four worlds, including Earth as a reference. Jupiter, the largest of the Jovian planets, is over 11 times the diameter of Earth. In fact, 1320 Earths could fit inside Jupiter. Saturn is slightly smaller, and Uranus and Neptune are somewhat smaller than Jupiter but still four times Earth's diameter. Beyond Neptune you will discover the Kuiper belt, a collection of icy planetesimals of varying sizes. At the end of this chapter you will learn about several of the larger bodies in this part of our solar system including Pluto, now classified as a dwarf planet.

Another common feature of Jovian planets is their ring system. The most obvious example of planetary rings is Saturn. If you have managed to view Saturn through a telescope you have witnessed a truly spectacular site. However, it's important to know that Jupiter, Uranus, and

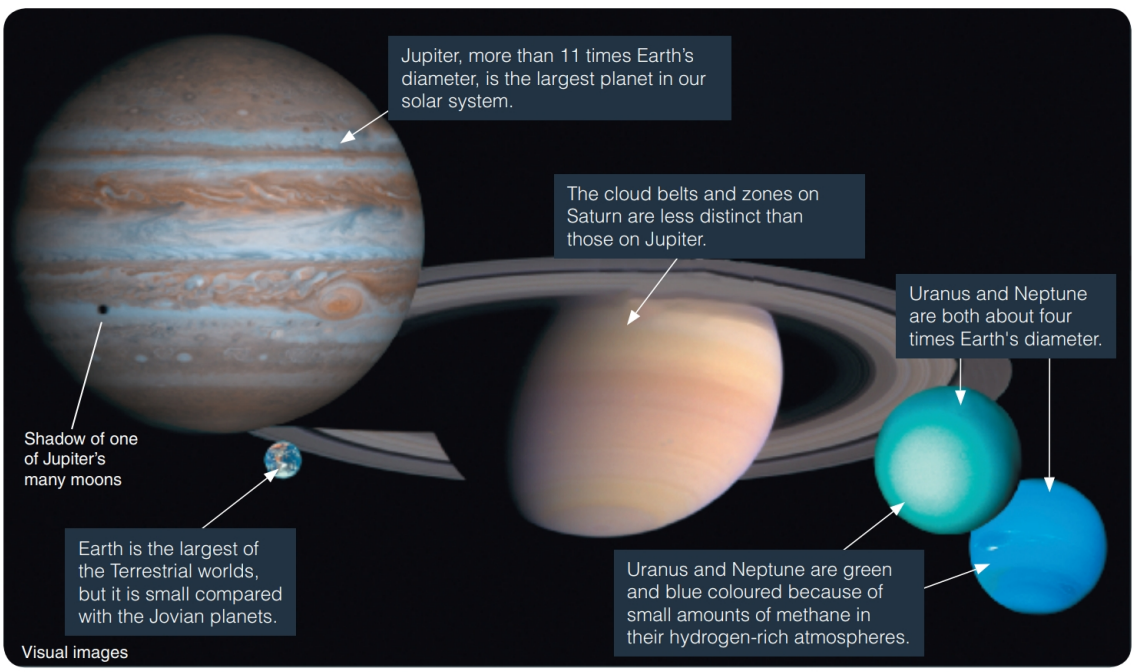


Figure 14.1 The four Jovian planets are massive, low-density worlds that have no solid surface on which to stand.

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CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Courtesy Brett Gladman

Brett J. Gladman

Brett J. Gladman

Canadian astronomer Brett J. Gladman is a professor at the University of British Columbia's Department of Physics and Astronomy in Vancouver. He holds the Canada Research Chair in Planetary Astronomy and the chair of the Science Advisory Council of the Canada-France-Hawaii Telescope on Mauna Kea in Hawaii.

Gladman's best-known work is in the area of dynamical astronomy in the solar system: planet formation, transport of meteorites between planets, the delivery of meteoroids from the main asteroid belt, and the possibility of the transport of life via this mechanism, known as panspermia. He is discoverer or co-discoverer of many astronomical bodies in the solar system: asteroids, Kuiper belt comets, and many moons of the giant planets. Gladman was awarded the H. C. Urey Prize by the Division of Planetary Sciences of the American Astronomical Society in 2002. Asteroid 7638 Gladman is named in his honour.

Neptune also have rings, but they are not easily detected from Earth and are not shown in Figure 14.1. As you study these worlds you will be able to compare four different sets of planetary rings.

Physical Characteristics

Characterizing Jovian atmospheres as extensive and gaseous is actually an oversimplification. Jupiter's gaseous atmospheres makes up only about 1 percent of its radius and this is the part that we see from here on Earth. This uppermost layer is comprised of hydrogen, for the most part, with smaller amounts of ammonia, ammonium hydrosulfide, phosphine, and water. We don't have to descend very deep in the gaseous atmosphere (about 300 km) before it becomes a liquid-conducting layer of hydrogen nuclei (protons, therefore) and free-moving electrons, called **liquid metallic hydrogen** (labelled "metallic" because the layer conducts heat and electricity just as metals do). This conducting layer that extends down to about 80 percent of Jupiter's radius is the source of the planet's huge magnetic field. The remaining planet's inner composition is largely unknown, although it is speculated that the central core may well be a loose rubble of rock and other compounds that formed the embryonic planetesimal during the early solar system. Saturn is probably quite similar in composition and structure, with slightly different hydrocarbon molecules in the upper atmosphere resulting in a more yellow-tan colouring. Given these recent findings these two largest planets should probably be referred to as *liquid giants* rather than *gas giants*. Uranus and Neptune are often referred to as *ice giants* because they formed farther away from the Sun where the temperature is lower and are, therefore, rich in water in both solid and liquid states. Clearly, then, no Jovian planet has a definite solid surface on which you could land a spacecraft or even go for a stroll.

14.2 Jupiter

Jupiter can be very bright in the night sky, and its cloud belts and four largest moons can be seen through even a small telescope. Jupiter is the largest and most massive of the Jovian planets—318 times more massive than Earth, and containing 71 percent of all the planetary matter in the entire solar system. It orbits the Sun at a distance of 5.2 AU, completing each orbit in about 11.9 years—which means that it goes through one zodiacal region per year, more or less. Despite the fact that Jupiter is the most massive of all the planets, its sidereal rotation period is a mere 10 hours, making its spinning rate the fastest of all the planets. Jupiter formed beyond the ice line where icy planetesimals could combine to grow quickly by gravitational collapse, pulling in gas, dust, and multiple smaller icy bodies as a smaller version of our own solar system. Consult the **Celestial Profiles** in Appendix C for more data about Jupiter.

As indicated in the previous section, the composition of Jupiter's atmosphere is a thin but visible layer of hydrogen mixed with various

liquid metallic hydrogen A form of liquid hydrogen that is a good electrical conductor; inferred to exist in the interiors of Jupiter and Saturn.

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magnetosphere The volume of space around a planet within which the motion of charged particles is dominated by the planetary magnetic field rather than the solar wind.

belt–zone circulation The atmospheric circulation typical of Jovian planets in which dark belts and bright zones encircle the planet parallel to its equator.

forward scattering The optical property of finely divided particles to preferentially direct light in the original direction of the light's travel.

Roche limit The minimum distance between a planet and its satellite so that the satellite can hold itself together by its own gravity. If a satellite's orbit brings it within the planet's Roche limit, tidal forces will pull the satellite apart.

hydrocarbon molecules, a conducting layer of metallic hydrogen (a denser and thicker layer with pressures so great that the hydrogen molecules break apart, becoming a sea of electrons and protons), all surrounding a core of heavier elements forming either a rubble of rock-like particles or a very hot soup-like conglomerate. In other words, if you were able to plunge deep into Jupiter's interior you would discover increasing gas density until you were sinking through a liquid, but you would never realize the transition from gas to liquid to the very thick and hot syrupy—but possibly chunky—soup at the core because the transitions occur very gradually. When you reached the centre you would find a temperature almost five times hotter than the surface of the Sun and a pressure of 50 million bar.

Jupiter's magnetic field results from such a large mass of conducting liquid combined with the planet's rapid rotation. Its magnetic field is 10 times stronger than Earth's, deflecting the solar wind and creating a huge region around Jupiter known as the **magnetosphere**. The strong magnetic field around Jupiter traps charged particles from the solar wind in radiation belts a billion times more intense than the Van Allen belts that surround Earth. Spacecraft that have flown through these regions received more than 1000 times the radiation that would have been lethal for a human.

Careful infrared measurements of the heat flowing out of Jupiter reveal that the planet emits about twice as much energy as it absorbs from the Sun. This energy is understood to be heat left over from the formation of the planet. In Chapter 12 you saw that Jupiter should have grown very hot when it formed, and some of that heat remains in its interior.

Study **Visualizing Astronomy 14.1, Jupiter's Atmosphere, Magnetosphere, and Rings**, and notice four important ideas:

1. The pattern of coloured cloud bands circling the planet, like stripes on a child's ball, is known as **belt–zone circulation**. This pattern is related to Jupiter's rapid rotation and to the high- and low-pressure areas in Jupiter's atmosphere.
2. The positions of the cloud layers are at certain temperatures within the atmosphere where ammonia (NH_3), ammonium hydrosulphide (NH_4SH), and water (H_2O) can condense.
3. Jupiter's extensive magnetosphere is responsible for auroras around the magnetic poles, similar to Earth's aurora borealis and aurora australis.
4. Jupiter's rings, discovered in 1979 by the *Voyager 1* space probe, are considerably fainter and less extensive than those of Saturn and relatively close to the planet, certainly within the Roche limit.

Jupiter's Rings

Galileo was the first to observe, in 1610, that Saturn had something resembling rings, although it wasn't until some 50 years later that more powerful telescopes provided a much clearer picture of these planetary adornments. However, it wasn't until 1979 that Jupiter's ring system was discovered when *Voyager 1* sent back photos during its grand tour of the solar system.

Jupiter's ring system is obviously relatively faint and consists mostly of dust and smoke-sized particles. This conclusion results mainly from observing the rings when they are illuminated from behind. This **forward scattering** of visible light indicates that the size of the ring particles must be about equal to the wavelengths of visible light, about the size of cigarette smoke.

The concept of the **Roche limit** is important in understanding the origin of the rings. The minimum distance from a planet within which a moon cannot hold itself together by its own gravity is called the Roche radius or limit. If a moon falls inside this limit, tidal forces become greater than the moon's gravity and pull the moon apart. This means, of course, that moons cannot form inside the Roche limit. All Jovian rings lie within the respective Roche limits, about 2.4 times a planet's radius. Remember that the Roche limit refers to natural satellites (moons) that are held together by their own gravity, whereas forces other than gravity hold spacecraft and orbiters together and, therefore, maintain their structure inside this limit.

This explains Jupiter's dusty rings. If a dust speck gets knocked loose from a larger rock inside the Roche limit, the rock's gravity cannot hold the dust speck. For that same reason, the billions of dust specks in the rings can't pull themselves together to make a moon because of tidal forces inside the Roche limit.

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The Jovian ring system has four main components: an inner doughnut-shaped collection of particles known as the halo ring; a relatively bright, thin main ring; and two wide, outer so-called gossamer rings, named for the moons from where their material comes: Amalthea and Thebe. The main and halo rings consist of dust ejected from the moons Metis and Adrastea. All of the ring material is continually being lost owing to two main mechanisms—sunlight pressure and Jupiter's strong magnetic field, which result in dislodging ring particles from their orbits causing them to slowly spiral down into the planet. At the same time the moons mentioned above supply new ring material through micrometeorite bombardment that erodes the surface of the moons.

The rings around Saturn, Uranus, and Neptune are known to be short-lived, and they also must be resupplied by new material, probably eroded from nearby moons. Besides supplying the Jovian rings with particles, moons confine the rings, keeping them from spreading outward and altering their shapes.

Jupiter's Family of Moons

Jupiter has four large moons and at least 63 smaller moons ranging in size from about 1 km radius to Ganymede's radius of 2634 km, the largest moon in the solar system. Most of the small moons are probably captured asteroids. The four largest moons (Figure 14.2), called the Galilean moons after their discoverer, Galileo, are clearly related to each other and probably formed with Jupiter as a mini solar system from the dust and gas circling this largest of all planets orbiting the Sun.

The outermost Galilean moons, Ganymede and Callisto, are about the size of Mercury, one and a half times the size of Earth's moon. Ganymede and Callisto have low densities of only 1.9 and 1.8 g/cm^3, respectively, meaning they must consist roughly of half rock and half ice. Observations of their gravitational fields by the *Galileo* spacecraft reveal that both moons have rocky and metallic cores and lower-density icy exteriors, so they both have differentiated. Both moons interact with Jupiter's magnetic field in a way that shows they probably have mineral-rich layers of liquid water 100 km or more below their icy crusts.

Callisto's surface and most of Ganymede's surface appear old because they are heavily cratered and very dark. The continuous blast of micrometeorites evaporates surface ice, leaving behind embedded minerals to form a dark skin like the grimy crust on an old snowbank—so surfaces get darker with age. More recent impacts dig up cleaner ice and leave bright craters, as on Callisto (see Figure 14.2). Ganymede has some younger, brighter grooved terrain believed to be systems of faults in the brittle crust. Some sets of grooves overlap other sets of grooves, suggesting extended episodes of geological activity.

The density of the next moon inward, Europa, is 3 g/cm^3, high enough to mean that the moon is mostly rock with a thin icy crust. The visible surface is very clean ice, contains very few craters, has long cracks in the icy crust, and has complicated terrain that resembles blocks of ice in Earth's Arctic Ocean (Figure 14.3). The lack of craters tells you that Europa is an active world where craters are quickly erased. In fact, Europa has the smoothest surface of any planet or moon in the solar system. The pattern of folds on its surface suggests that the icy crust breaks as the moon is flexed by tides (see Chapter 3). Europa's gravitational influence on the *Galileo* spacecraft reveals there is a liquid-water ocean, perhaps 200 km deep, below the 10- to 100-km-thick

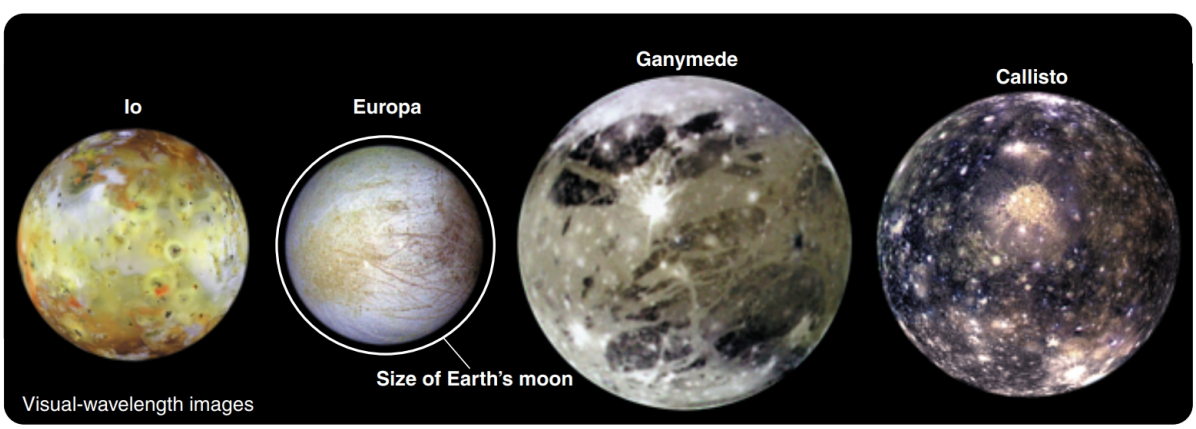
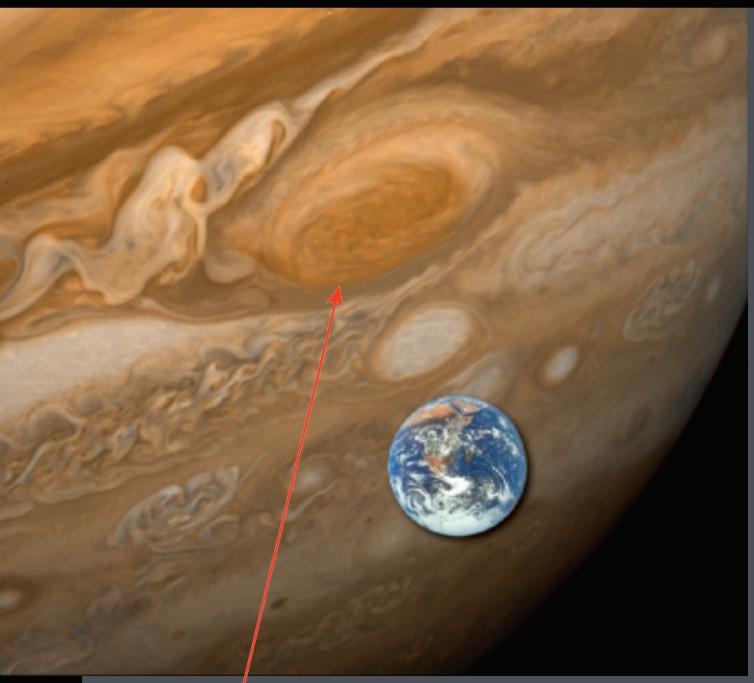


Figure 14.2 Colour-enhanced visual-wavelength image of Jupiter's Galilean moons.

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Visualizing Astronomy 14.1

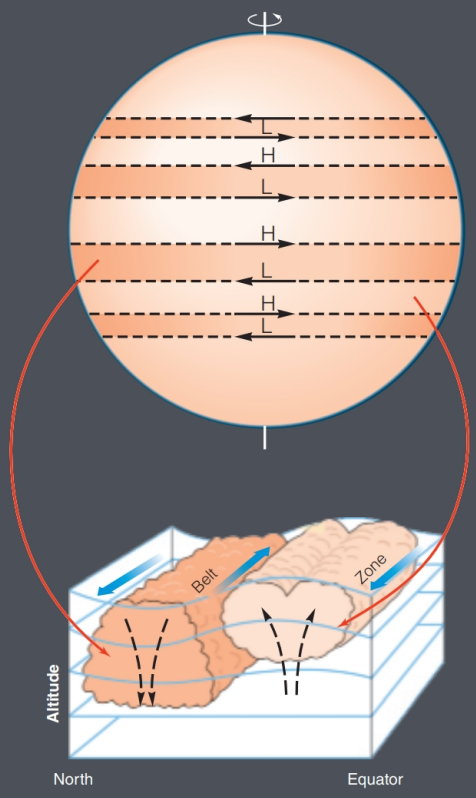
Jupiter's Atmosphere, Magnetosphere, and Rings



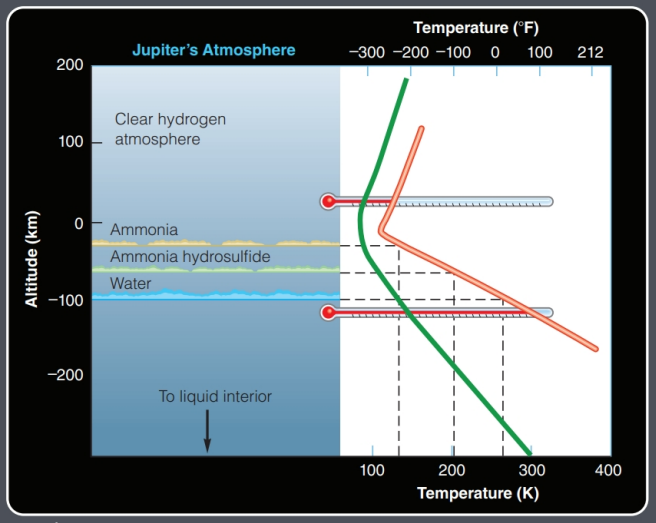
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1 The visible clouds are not at the top of the atmosphere; an upper atmosphere of clear hydrogen and helium extends far above the cloud tops. Jupiter's atmosphere makes up only 1 percent of its radius. Major spots on Jupiter, like the Great Red Spot, are embedded circulating storms. They can remain stable for decades or even centuries.



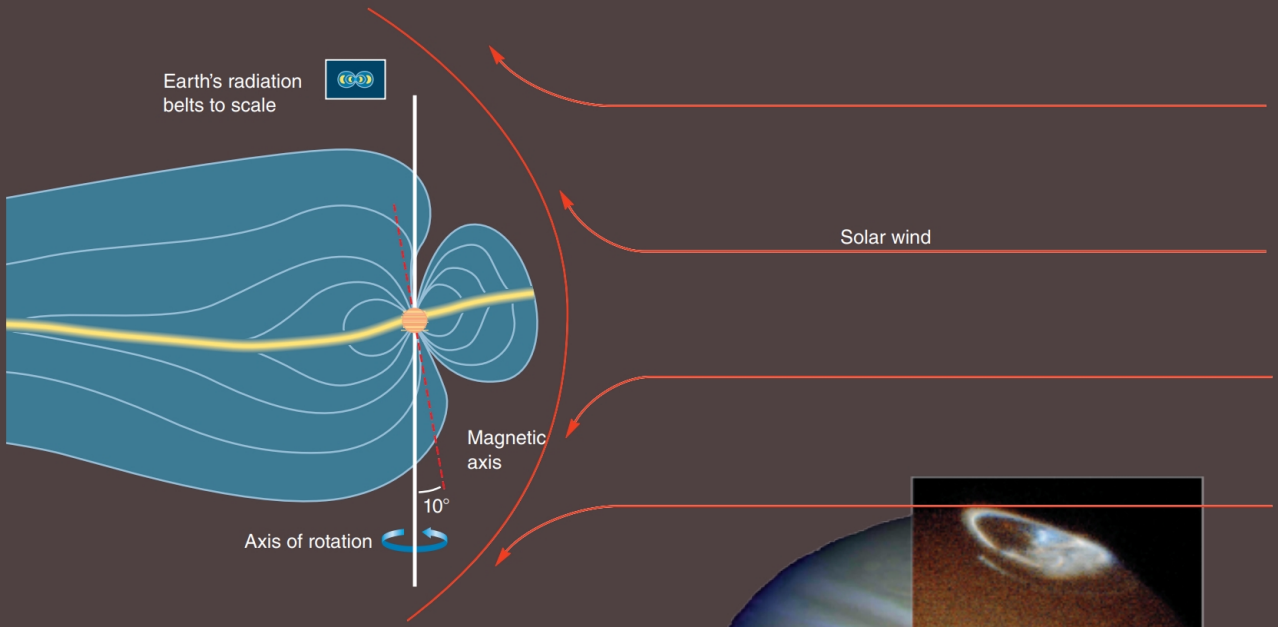
1a Cloud belts and zones circle Jupiter like stripes on a ball. This form of atmospheric circulation is belt–zone circulation. The poles and equator on Jupiter are about the same temperature, perhaps because of heat rising from the interior. Because of that, and also because of Jupiter's rapid rotation, instead of wave-shaped winds as on Earth, Jupiter's high- and low-pressure areas are stretched into belts and zones parallel to the equator. Zones are brighter than belts because rising gas forms clouds high in the atmosphere where sunlight is stronger and reflected back to outside viewers.



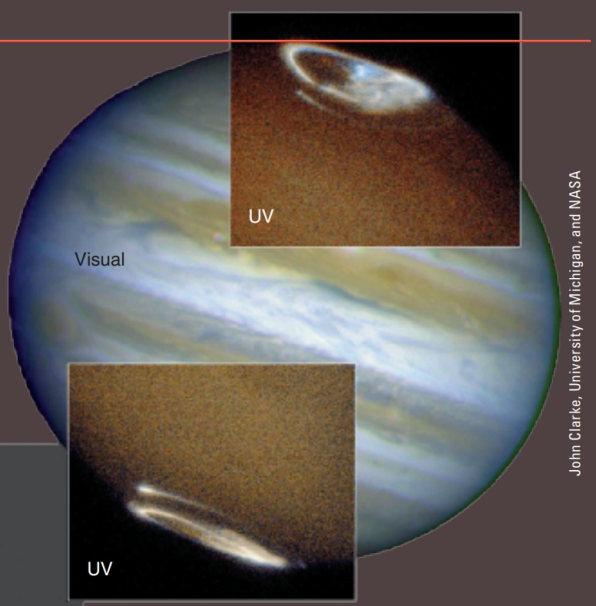
2 Jupiter's cloud layers lie at certain temperatures within the atmosphere where ammonia (NH_3), ammonium hydrosulphide (NH_4SH), and water (H_2O) can condense into droplets. If you could put thermometers into the different levels of the atmosphere, you would discover that the temperatures rise as you descend beneath the uppermost clouds, represented for Jupiter by the solid orange line. Because Saturn is farther from the Sun, its temperature is colder, shown by the green line. The cloud layers on Saturn form at the same temperature as the cloud layers on Jupiter, but they are deeper in Saturn's hazy atmosphere.

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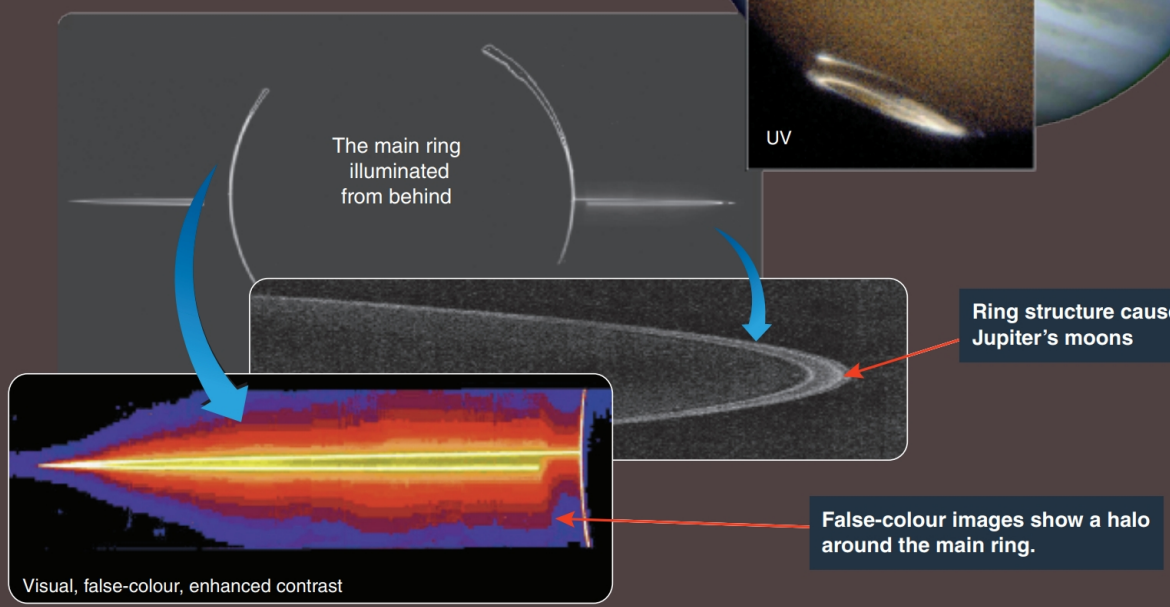
3 A planet's magnetic field deflects the solar wind and dominates a volume of space around the planet called the magnetosphere. Jupiter's magnetosphere is 100 times larger than Earth's. If you could see it in the sky, it would be 6 times larger than the full Moon.



4 As you saw with Earth in Chapter 5, interations between Jupiter's magnetic field and the solar wind generate powerful electric currents that flow around the planet's magnetic poles. These aurorae on Jupiter are larger in diameter than Earth, and are confined to the north and south magnetic poles, as shown in these ultraviolet images. Jupiter's rings, discovered in 1979 by the *Voyager I* space probe, are relatively close to the planet.

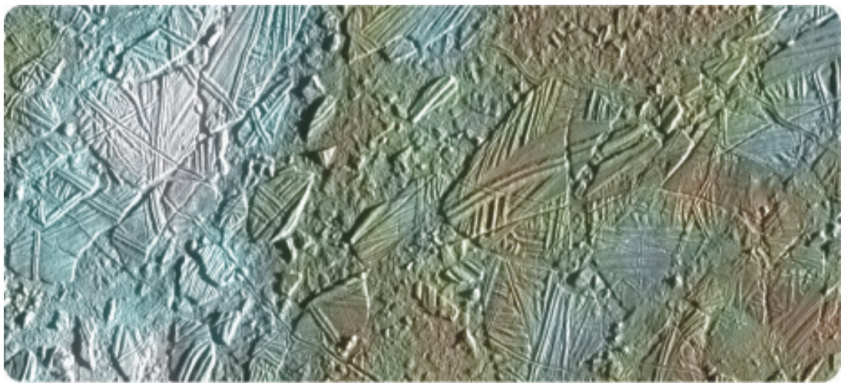


John Clarke, University of Michigan, and NASA



Panel a and c: NASA/JPL-Caltech/Univ. of Arizona;
Panel b: NASA/JPL-Caltech/Cornell Univ.

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NASA

Figure 14.3 Like icebergs on the Arctic Ocean, blocks of crust on Europa appear to have floated apart. The blue icy surface is stained brown by mineral-rich water venting from below the crust. White areas are ejecta from the impact that formed the nearby crater Pwyll.

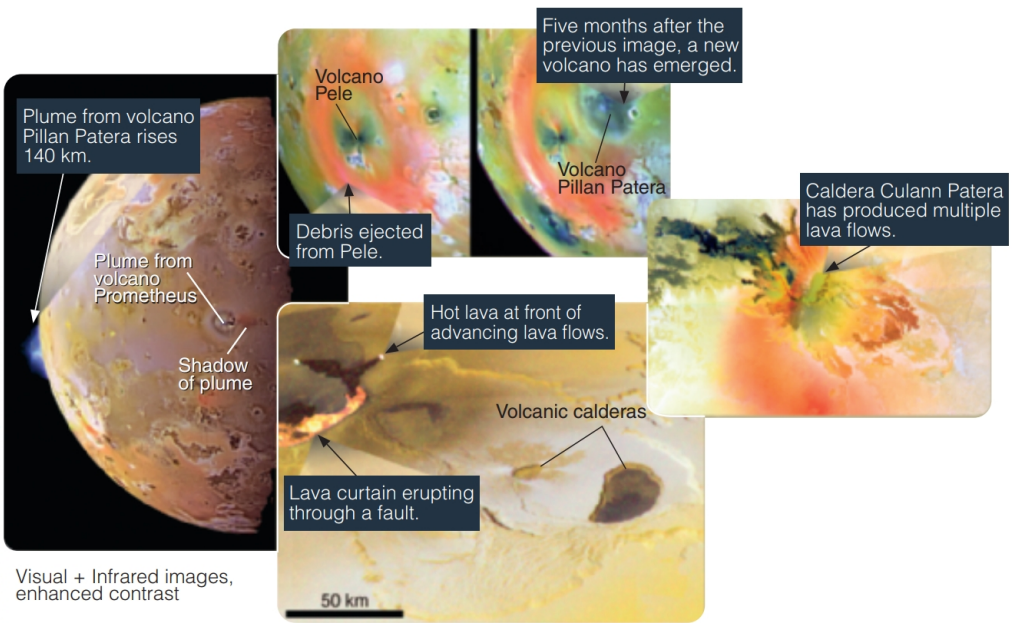
ash falls back to bury the surface at a rate of a few millimetres a year. This explains why you see no impact craters on Io—they are covered up as fast as they form. Io's density is 3.6 g/cm^3, which indicates it does not consist of ice, but rather rock and metal. Its gravitational influence on the passing *Galileo* spacecraft revealed that it is differentiated into a large metallic core, a rocky mantle, and a low-density crust.

The activity we see in the Galilean moons must be driven by energy flowing outward, yet these objects are too small to have remained hot from the time of their formation. Io's volcanism seems to be driven by **tidal heating**. Io follows a slightly eccentric orbit caused by its interactions with the other moons. Jupiter's gravitational field flexes Io with tides, and the resulting friction heats its interior. That heat flowing outward causes the volcanism. Europa is not as active as Io, but it too must have a heat source, presumably tidal heating. Ganymede is no longer active, but when it was younger it must have had internal heat to break the crust and produce the grooved terrain.

tidal heating The heating of a planet or satellite because of friction caused by tides.

crust. You will not be surprised to learn that NASA recently (2016) announced that Hubble has imaged what appear to be 200-km-high water vapour plumes emanating from Europa's surface.

Images from spacecraft reveal that Io, the innermost of the four Galilean moons, has over 150 volcanic vents on its surface (see Figure 14.4). These active volcanoes throw sulphur-rich gas and ash high above the surface; the



Left panel: NASA/JPL-Caltech/University of Arizona; Top-centre and right panels: NASA/JPL-Caltech/ASU; Bottom panel: NASA/JPL-Caltech

Figure 14.4 These colour images of volcanic features on Io were produced by combining visual and near-infrared images and then digitally enhancing the colour. To human eyes, most of Io would look pale yellow and light orange.

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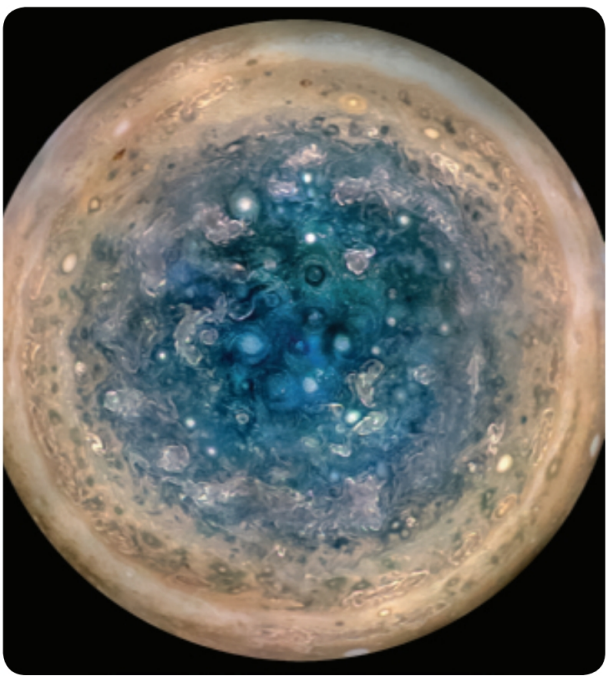
Exploration

Both flyby and orbiting spacecraft have visited Jupiter. The first missions were *Pioneer 10* (1973) and *Pioneer 11* (1974),which provided the first close-up images of Jupiter and discovered its magnetosphere and some information about the planet's interior. *Voyager 1* and *2* followed in 1979 and studied the Galilean moons, never-before-seen rings (mentioned earlier) and radiation belts. Discovering Io's volcanic activity and Europa's smooth water ice surface was a definite bonus for the *Voyager* missions. This aptly demonstrates that much science can be learned through robotic (unmanned) spacecraft. Other spacecraft (*Cassini*, *Ulysses*, and *New Horizons*) have all completed flybys of Jupiter, using its huge mass to redirect their trajectories to other destinations but making use of proximity to Jupiter to study it further with better instrumentation than the earlier flyby missions.

Galileo was the first spacecraft to settle into orbit around Jupiter, studying the planet and its major moons for almost 8 years. The list of discoveries made by *Galileo* is lengthy but includes those already mentioned in previous sections: a flyby of the asteroid Gaspra, the first discovery of an asteroid moon (Dactyl) around Ida, and detailed studies of Jupiter's atmosphere. Also, it observed the collision of the comet Shoemaker-Levy 9 with Jupiter. *Galileo* ended its mission with a planned plunge into Jupiter's atmosphere in order not to contaminate Jupiter's moons with Earthly bacteria.

The second orbiter to visit Jupiter, *Juno*, entered into orbit in 2016. It is expected to collect scientific information for two or three years, although this mission may be extended, as often happens with NASA missions. *Juno*'s orbits take it directly over both Jupiter's north and south poles, unlike any previous spacecraft, revealing unexpected polar weather systems. Shown in Figure 14.5 are white oval-shaped cyclones moving randomly over the south polar region against a colour-enhanced blue background.

Planned missions include European Space Agency's *Jupiter Icy Moon Explorer (JUICE)*, which will study the crusts and putative subsurface oceans of the three larger Galilean moons. Also, NASA is planning the *Europa Clipper* to be launched in the mid-2020s to explore Europa's habitability and potential sites for a robotic lander.



NASA/JPL-Caltech/SwRI/MSSS/Betsy Asher Hall/Gervasio Robles

Figure 14.5 Jupiter's south pole, photographed by Juno from an altitude of 52 000 km. The oval features are cyclones, up to 1000 km in diameter. Many images taken with the JunoCam instrument on three separate orbits were combined to show all areas in daylight, enhanced colour, and stereographic projection.

14.3 Saturn

The Roman god Saturn, god of agriculture and plenty, was once celebrated in a week-long festival, Saturnalia, around the winter solstice in late December. Christians eventually took over the holiday to celebrate the birth of Christ.

Saturn is most famous for its beautiful and fascinating rings, which are easily visible through the telescopes of modern amateur astronomers. Large Earth-based telescopes have explored the planet's atmosphere, rings, and moons. Saturn's orbital radius is almost twice that of Jupiter, and Saturn takes almost 30 years to orbit the Sun. Similar to Jupiter, Saturn's rotation rate is quite short: 10.7 hours. Interestingly, Saturn's density is 0.69 g/cm^3, meaning that it would float on Lake Superior—although the lake would have to be considerably larger than it is now. The two *Voyager* spacecraft flew past Saturn in 1979, and the *Cassini* spacecraft went into orbit around Saturn in 2004 on an extended exploration of the planet, its rings, and its moons. Consult the **Celestial Profiles** in Appendix C for more data.

In the opening illustration for this chapter, the belt–zone circulation of Saturn appears only faintly, but images from *Voyager*, the Hubble Space Telescope, and *Cassini* show that the belts and zones are present and that the associated winds blow up to three times faster than

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on Jupiter. Belts and zones on Saturn are less visible than on Jupiter because they occur deeper in the cold atmosphere, below a layer of methane haze.

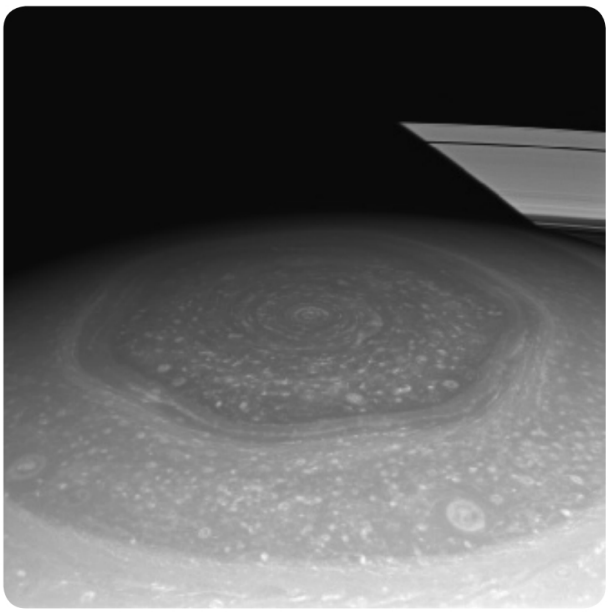
The low density of Saturn suggests that it is, like Jupiter, rich in hydrogen and helium. As many photographs show, Saturn is the most oblate of the planets, which tells you that its interior is mostly liquid and has a small core of heavy elements. Because its internal pressure is lower than that of Jupiter, Saturn has less liquid metallic hydrogen than Jupiter. Perhaps that is why Saturn's magnetic field is 20 times weaker than Jupiter's. Like Jupiter, Saturn radiates more energy than it receives from the Sun, and models predict that it has a very hot interior.

However, it is Saturn's strange north pole hexagonal atmospheric pattern that has mystified astronomers since it was first observed by the *Voyager* spacecraft and more recently by *Cassini* in greater detail. Shown in Figure 14.6 is the almost precise geometric pattern of six apparently equal sides of atmospheric turbulence about 30 000 km wide, roughly the same size as Jupiter's Great Red Spot. Various theories have been proposed to explain this phenomenon but none have been confirmed so far.

Saturn's Rings

If you study **Visualizing Astronomy 14.2, The Ice Rings of Saturn**, you will understand the composition of the rings, how their structure is influenced by some of Saturn's small moons, and their physical dimensions:

1. The rings are made up of billions of ice particles, each in its own orbit around the planet. The ring particles you observe can't be as old as Saturn. The rings must be replenished now and then by impacts on Saturn's moons or other processes. The same is true of the rings around the other Jovian planets.
2. The gravitational effects of small moons can confine some rings in narrow strands or keep the edges of rings sharp. Moons can also produce waves in the rings that are visible as tightly wound ringlets.
3. The ring particles are confined in a thin layer in Saturn's equatorial plane, spread among small moons and confined by gravitational interactions with larger moons. The rings of Saturn, and the rings of the other Jovian worlds, are created by and controlled by the planet's moons. Without the moons, there would be no rings.



NASA/JPL-Caltech/Space Science Institute

Figure 14.6 *Cassini*'s view of Saturn's north pole showing the strange hexagonal pattern of atmospheric storms. Part of Saturn's rings are shown in the upper-right background.

Saturn's Family of Moons

Like Jupiter, Saturn has over 60 moons. Most are small, from less than 1 km to about 1150 km in diameter. Their densities indicate they are various mixtures of rock and ice and are probably captured bodies. One moon, Titan, is very large, even larger than the planet Mercury and with a density similar to Jupiter's Galilean moons. You would expect, then, that Titan's structure should be similar, with a rocky core surrounded by a thick mantle of ice. Cassini's measurements indicate that there may be a liquid layer underneath the icy mantle consisting of liquid water mixed with ammonia (the presence of ammonia would allow water to remain liquid at very low temperatures).

There are many interesting features of Titan. Being large and sufficiently cold it has retained an atmosphere—the only moon to have an atmosphere of any significance. In fact, it is almost 1.5 times denser and more extensive than Earth's atmosphere; however, its composition is essentially nitrogen with small amounts of argon and methane and other hydrocarbons (see Figure 14.7).

Titan's surface is mainly composed of ices of water and methane at –180°C. The *Cassini* spacecraft dropped the *Huygens* probe into the atmosphere of Titan and it photographed dark drainage channels, suggesting that liquid methane falls as rain that drains into the lowlands. Such methane downpours may be rare, however. No direct evidence of liquid methane was detected as the probe descended, but later radar images made by the

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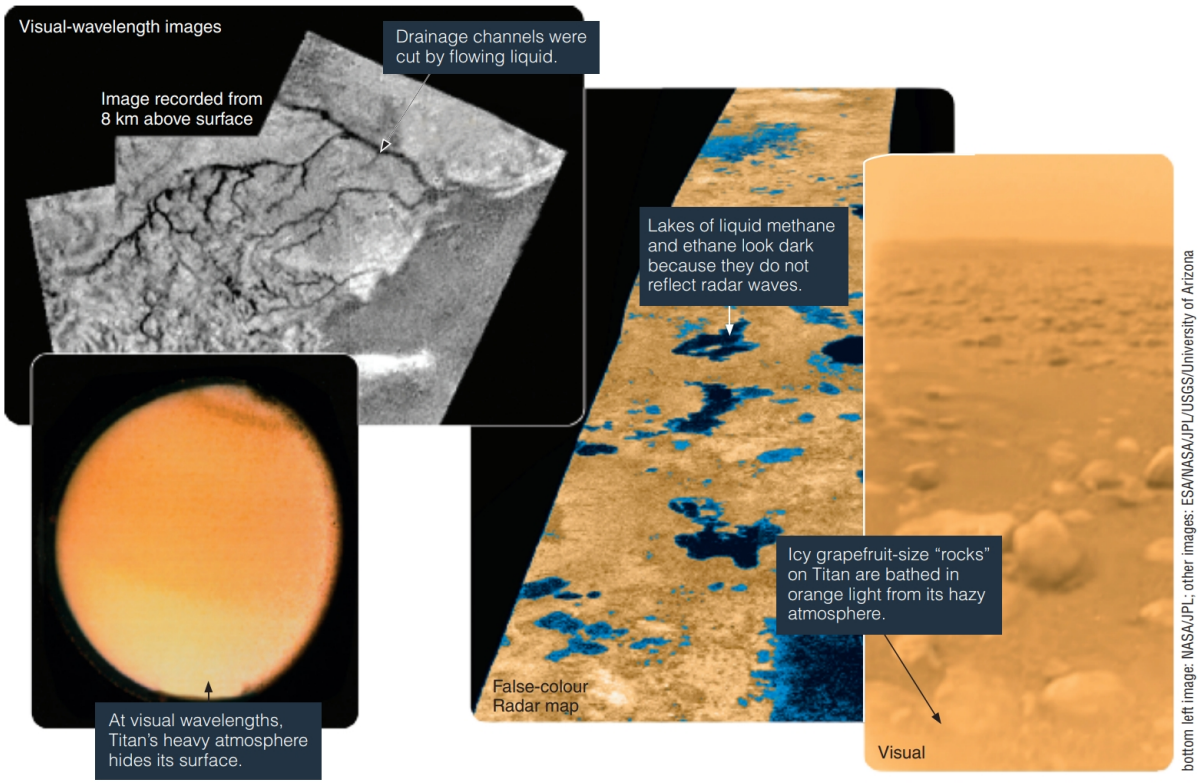


Figure 14.7 As the *Huygens* probe descended by parachute through Titan's smoggy atmosphere, it photographed the surface from an altitude of 8 km. Although no liquid was present, dark drainage channels were observed leading into the lowlands. Radar images reveal lakes of liquid methane and ethane around the poles. Once the *Huygens* probe landed on the surface, it radioed back photos showing a level plain and chunks of ice surrounded by a moving liquid.

Cassini orbiter have detected what appear to be lakes, presumably containing liquid methane. One such lake, Ontario Lacus, has a surface area about 20 percent of its namesake (Lake Ontario) and a depth of less than 10 m, and it could be composed of methane, ethane, and propane—although recent measurements suggest it may be more like a mudflat. Infrared images suggest the presence of methane volcanoes that replenish the methane in the atmosphere, so Titan must have some internal heat source to power the activity.

Most of the remaining moons of Saturn are small and icy, have no atmosphere, and are heavily cratered. Most have dark, ancient surfaces. However, Enceladus, Saturn's sixth-largest moon, remains geologically active due to tidal heating. Some parts of its surface contain up to 1000 times fewer craters than other regions, and infrared observations show that its south polar region is unusually warm. Furthermore, *Cassini* discovered water and ice-rich geyser-like jets venting from cryovolcanoes around the south pole (Figure 14.8). Analysis of these jets has revealed not only water vapour but also other volatiles, including sodium chloride crystals. A portion of this material falls back onto the moon's surface as snow; the reminder escapes into space, feeding Saturn's E ring.

Exploration

Around 1980, *Pioneer 11*, *Voyager 1*, and *Voyager 2* all executed flyby missions of Saturn. High-resolution pictures of both Saturn and various moons were taken for the first time, and the missions resulted in an increased knowledge of Titan's atmosphere. Small gaps in Saturn's rings were revealed, especially the now well-known Keeler gap.

The only other Saturnian explorer, *Cassini*, turned out to be a huge success. Initially the mission, which entered into orbit around Saturn in mid-2004 and was planned to be four years long, was extended twice before being terminated by flying into Saturn's atmosphere in September 2017. Many of its discoveries have been outlined in this chapter.

At this time there are no confirmed future missions to Saturn, although any such missions are likely to include both Enceladus and Titan where the intention will be to study their subsurface oceans.

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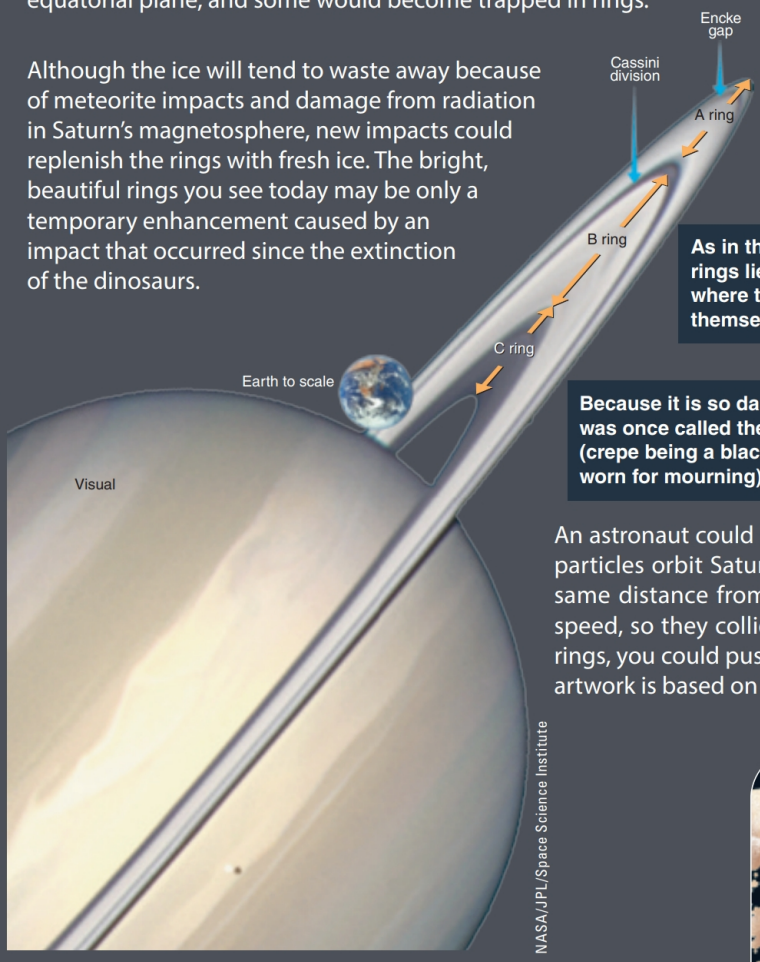
Visualizing Astronomy 14.2

1 THE ICE RINGS OF SATURN

The brilliant rings of Saturn are made up of billions of ice particles ranging from microscopic specks to chunks bigger than a house. Each particle orbits Saturn in its own circular orbit. Much of what planetary scientists know about the rings has been learned from the *Voyager 1* and *2* flybys and the *Cassini* orbiter. From Earth, astronomers see three rings labelled A, B, and C. *Voyager* and *Cassini* images reveal over a thousand ringlets within the rings.

Saturn's rings can't be leftover material from the formation of Saturn. The rings are made of ice particles, and the planet would have been so hot when it formed that it would have vaporized and driven away any icy material. Rather, the rings must be debris from collisions between Saturn's icy moons and passing comets or asteroids. Impacts large enough to scatter ice throughout the Saturn system are estimated to occur every 100 million years or so. The ice would quickly settle into the equatorial plane, and some would become trapped in rings.

Although the ice will tend to waste away because of meteorite impacts and damage from radiation in Saturn's magnetosphere, new impacts could replenish the rings with fresh ice. The bright, beautiful rings you see today may be only a temporary enhancement caused by an impact that occurred since the extinction of the dinosaurs.



As in the case of Jupiter's ring, Saturn's rings lie inside the planet's Roche limit where the ring particles cannot pull themselves together to form a moon.

Because it is so dark, the C ring was once called the crepe ring (crepe being a black-dyed fabric worn for mourning).

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1a An astronaut could swim through the rings. Although the particles orbit Saturn at high velocity, all particles at the same distance from the planet orbit at about the same speed, so they collide gently at low velocities. If you could visit the rings, you could push your way from one icy particle to the next. This artwork is based on a model of particle sizes in the A ring.



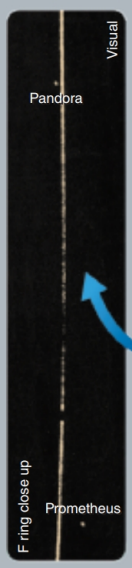
The C ring contains boulder-size chunks of ice, whereas most particles in the A and B rings are more like golf balls, down to dust-size ice crystals. Further, C ring particles are less than half as bright as particles in the A and B rings. *Cassini* observations show that the C ring particles contain less ice and more minerals.

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2

Because of collisions among ring particles, planetary rings should spread outward. The sharp outer edge of the A ring and the narrow F ring are confined by **shepherd satellites** that gravitationally usher straying particles back into the rings.

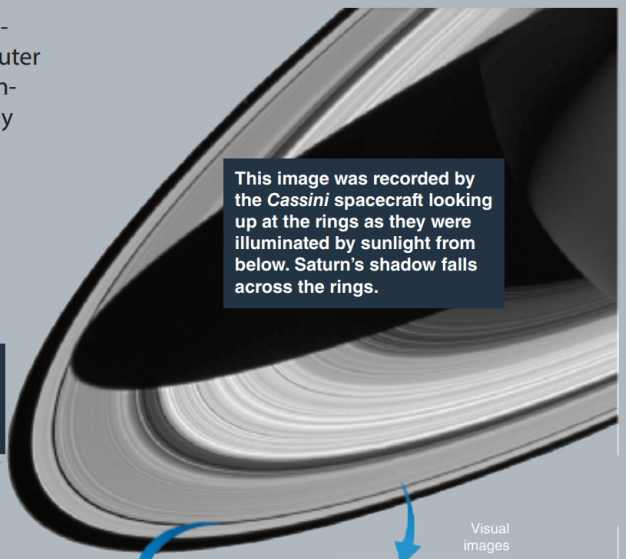
Some gaps in the rings, such as the Cassini division, are caused by resonances with moons. A particle in the Cassini division orbits Saturn twice for each orbit of the moon Mimas. On every other orbit, the particle feels a gravitational tug from Mimas. These tugs always occur at the same places in the orbit and force the orbit to become slightly elliptical. Such an orbit crosses the orbits of other particles, which results in collisions, and that removes the particle from the gap.



The F ring is clumpy and sometimes appears braided because of two shepherd satellites.

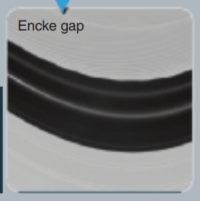


This image was recorded by the *Cassini* spacecraft looking up at the rings as they were illuminated by sunlight from below. Saturn's shadow falls across the rings.



Visual images



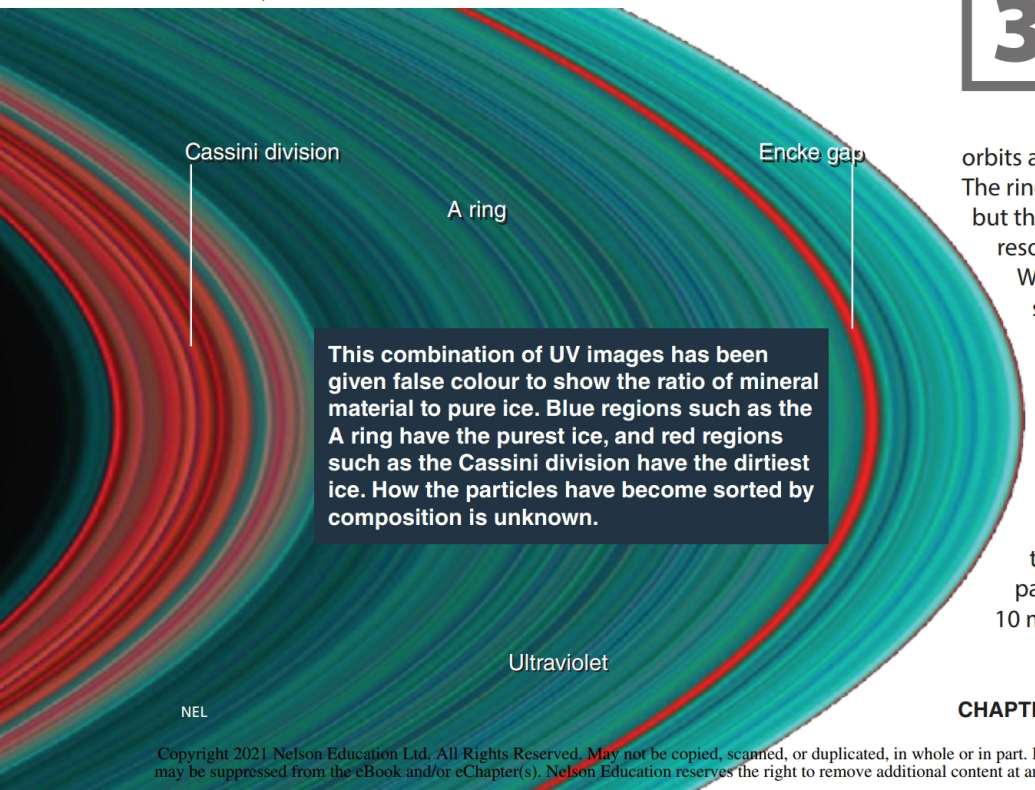


The Encke gap is not empty. Note the ripples at the inner edge. A small moon orbits inside the gap.

Saturn does not have enough moons to produce all of its ringlets by resonances. Many are the result of tightly wound density waves, something like the spiral arms found in disk galaxies.

NASA/ JPL/Space Science Institute

NASA/ JPL/ Space Science Institute



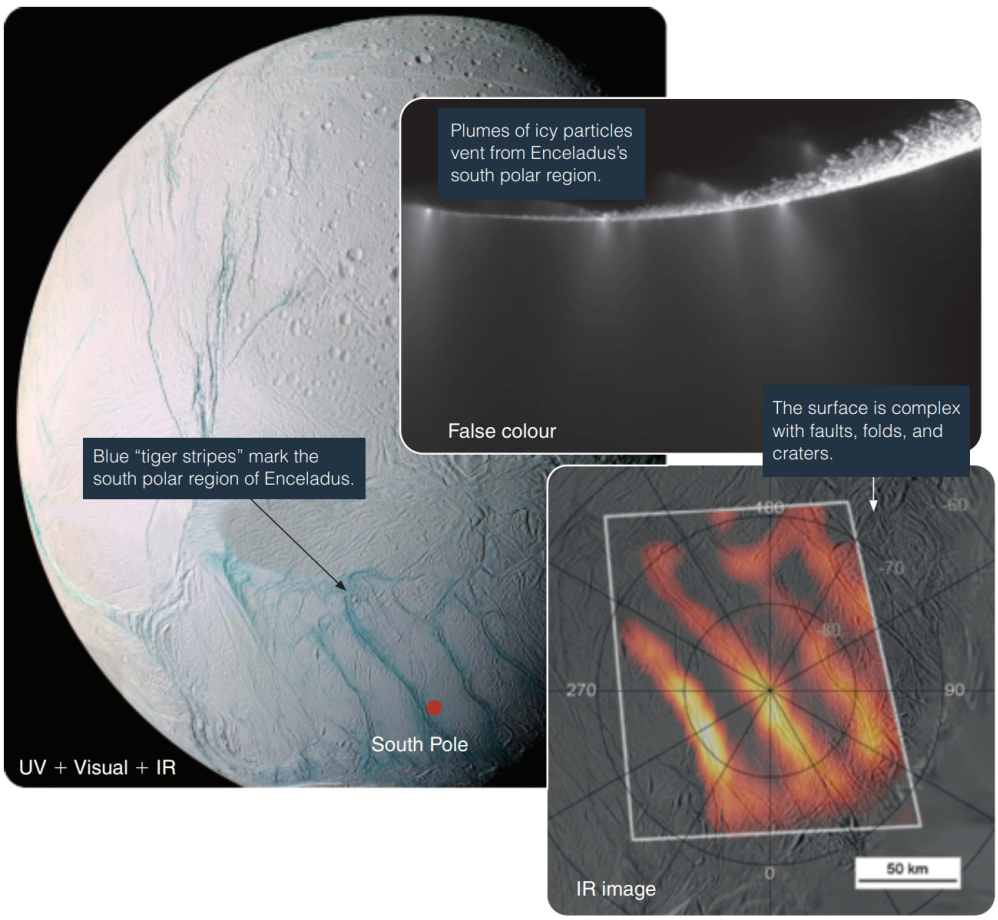
This combination of UV images has been given false colour to show the ratio of mineral material to pure ice. Blue regions such as the A ring have the purest ice, and red regions such as the Cassini division have the dirtiest ice. How the particles have become sorted by composition is unknown.

3

How do moons happen to be at just the right places to confine the rings? That puts the cosmic cart before the horse. The ring particles get caught in the most stable orbits among Saturn's innermost moons. The rings push against the inner moons, but those moons are locked in place by resonances with larger, outer moons. Without the moons, the rings would spread and dissipate.

Saturn's rings are a very thin layer of particles and nearly vanish when the rings turn edge-on to Earth. Although ripples in the rings may extend for hundreds of metres above and below the midplane, the sheet of particles may be only about 10 metres thick.

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Figure 14.8 Saturn's moon Enceladus is venting water, ice, and organic molecules from geysers near its south pole. A thermal infrared image reveals internal heat leaking to space from the "tiger stripe" cracks where the geysers are located.

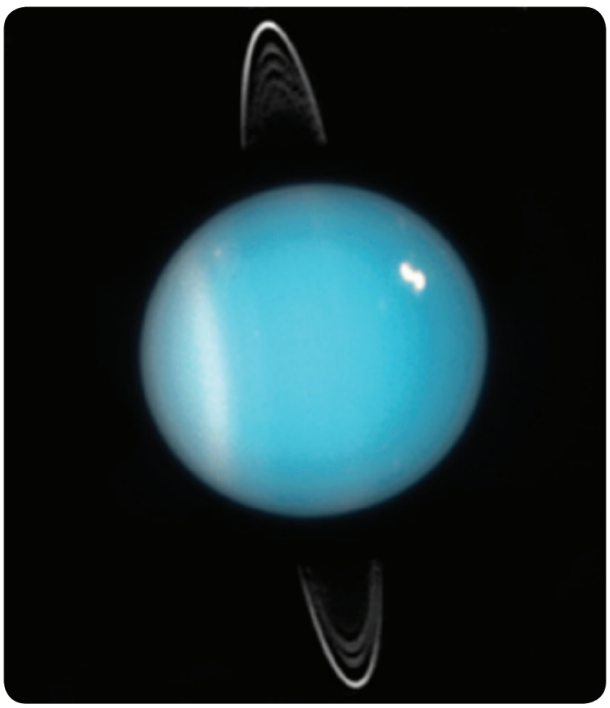
14.4 Uranus and Neptune: Ice Giants

Uranus and Neptune, the seventh and eighth planets from the Sun, are similar to each other in size and composition but are sufficiently different from the gas giants—Jupiter and Saturn—that they are often referred to as ice giants. This should tell you that these planets are far enough from the Sun to have ice mixtures below their thick atmospheres that consist mainly of hydrogen, helium, and small amounts of methane. Uranus has the coldest atmospheric temperature in the solar system at 49 K, although Neptune's atmospheric temperature is a close second at 55 K. The only spacecraft to visit the ice giants was *Voyager 2*, giving us the only close-up views of Uranus and Neptune (see Figures 14.9 and 14.10). The blue shades of both planets are due to the methane in their atmospheres, although the deeper blue colour of Neptune is due to some other unknown hydrocarbon constituent.

The scientist William Herschel, a German expatriate living in England, discovered Uranus in 1781. He named it George's Star, in honour of his patron English King George III. European astronomers, especially the French, refused to accept a planet named after an English king so they called it Herschel. Years later, German astronomer J. E. Bode suggested Uranus, the oldest of the Greek gods. Uranus orbits the Sun at an average of 19.2 AU, almost twice as far away as Saturn; once again we see how greatly spaced the Jovian planets are compared to the Terrestrial planets. An interesting feature of Uranus's rotation is that it is inclined to the ecliptic at about 98°, meaning that it actually rotates backward while appearing to "roll" along its orbit.

Travelling another 10 AU from Uranus, you reach the orbit of the outermost major planet in our solar system, Neptune. Interestingly, Neptune is the only planet in the solar system to be found by mathematical calculations (rather than by empirical observation). Astronomers noticed slight deviations in Uranus's orbit and posited they must be due to small gravitational perturbations owing to

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NASA, ESA, and M. Showalter (SETI Institute)

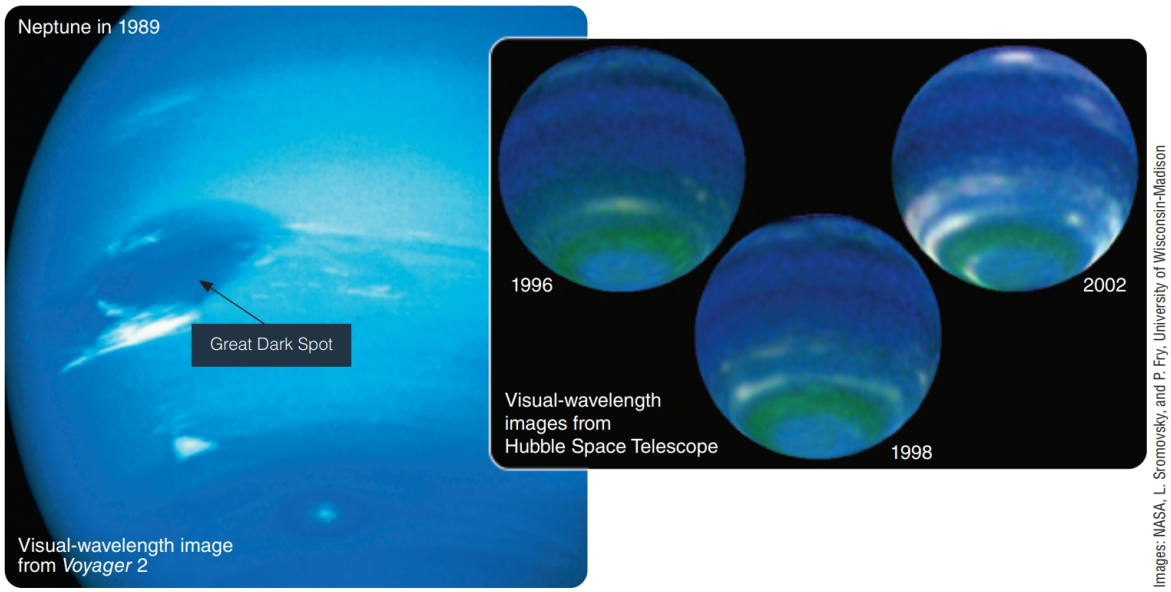
Figure 14.9 Uranus in 2005. Rings, southern collar, and a bright cloud in the northern hemisphere are visible.

the presence of an unknown planet. British astronomer John Couch Adams and French astronomer Urbain Le Verrier independently calculated the existence and location of Neptune based on these irregularities in Uranus's orbit. Neptune was discovered in 1846 by Frenchman Johan Galle. Astronomers named it after the god of the sea because Neptune looks like a tiny blue dot with no visible cloud features. When *Voyager 2* flew by Neptune in 1989 the large atmospheric feature now known as the Great Dark Spot (GDS), similar in size to the Great Red Spot on Jupiter, was noticed for the first time. About the size of Earth, the GDS appears to be an atmospheric circulation such as a cyclone or hurricane. Smaller spots have been visible in Neptune's atmosphere in recent years. More recently, the Hubble Space Telescope has photographed Neptune and found that the Great Dark Spot is gone, but new cloud formations have appeared. Clearly weather patterns on Neptune are quite variable.

ovoid The oval features found on Miranda, a satellite of Uranus.

Ice Giant Moon Systems

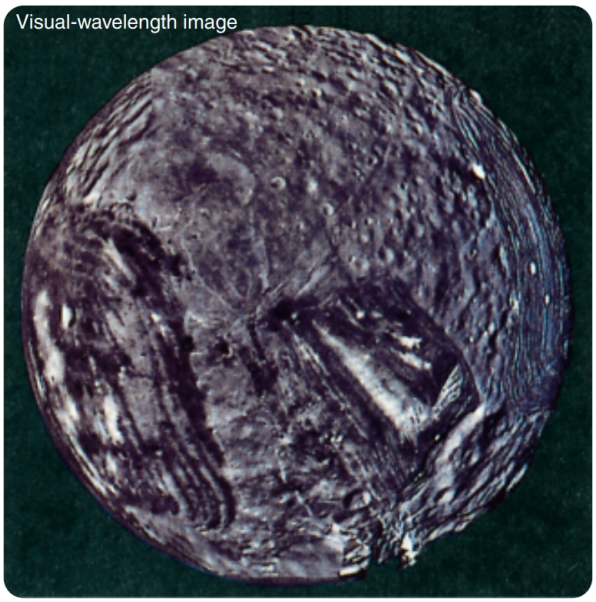
Uranus has 27 moons, although all but five are small, most having diameters less than 100 km. The five major moons of Uranus are smaller than Earth's moon and have old, dark, cratered surfaces. A few have deep cracks, produced, perhaps, when the interior froze and expanded. In some cases, liquid water "lava" appears to have erupted and smoothed over some regions. Miranda, the innermost moon, is only 14 percent the diameter of Earth's moon, but its surface is oddly marked by grooves called **ovoids** (Figure 14.11). These may have been caused by internal



Images: NASA, L. Sromovsky, and P. Fry, University of Wisconsin-Madison

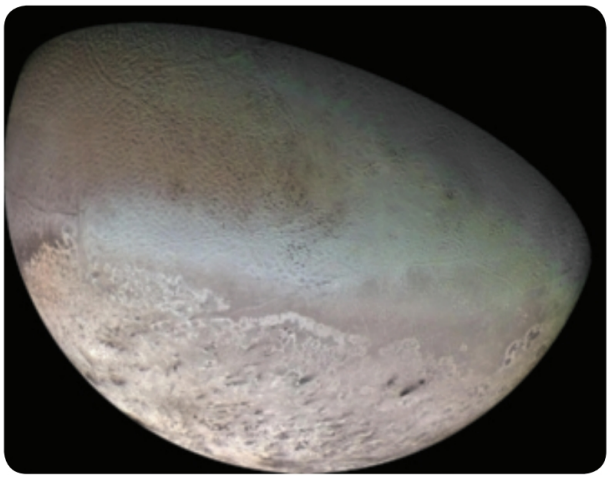
Figure 14.10 Neptune's axis is inclined almost 29° to its orbit. It experiences seasons that each last about 40 years. Since *Voyager* visited in 1989 spring has come to the southern hemisphere and the weather has clearly changed, which is surprising because sunlight at Neptune is 900 times dimmer than at Earth.

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NASA

Figure 14.11 Geological activity on Uranus's moon Miranda. The face of Miranda is marked by ovoids, which are believed to have formed when internal heating caused slow convection in the ice of the moon's mantle. Note the 5-km-high cliff at the lower right edge of the moon.



NASA/JPL/USGS

Figure 14.12 *Voyager 2* took this colour mosaic of Triton in 1989 during its flyby of the Neptune system. The bottom portion is a huge south polar cap consisting of nitrogen ice with small amounts of methane ice, which have reacted with sunlight to form pink or red compounds. The dark smudges are believed to be an icy, and perhaps carbonaceous, dust deposited from huge geyser-like plumes, some of which were found to be active during the *Voyager 2* flyby. The greenish areas dominating the upper half include what is known as the cantaloupe terrain, whose origin is unknown.

heat driving convection in the icy mantle. By counting craters on the ovoids, astronomers conclude that the entire surface is old, and the moon is no longer active. The International Astronomical Union (IAU) has adopted the practice that newly discovered moons of Uranus are to be named after characters in either Shakespeare's plays or in Pope's "The Rape of the Lock," following a trend established by John Herschel, son of William Herschel, discoverer of Uranus. So far only Ariel, Umbriel, and Belinda have names from Pope; all the rest are names from Shakespearian literature.

Neptune has 14 known moons, not-surprisingly named after water deities in Greek mythology. Most are small, asteroid-like bodies, but two in particular are larger. Nereid, about one-tenth the size of Earth's moon, follows a large, elliptical orbit, taking about an Earth year to orbit Neptune once. Triton, about 80 percent the size of Earth's moon, orbits Neptune backward—clockwise as seen from the north. These odd orbits suggest that the system was disturbed long ago in an interaction with some other body, such as a massive object.

Triton's atmosphere of nitrogen and methane is about 10^5 times less dense than Earth's with a temperature of 36 K. A significant part of Triton is ice, and deposits of nitrogen mixed with methane frost are visible at the southern pole (Figure 14.12). Many features on Triton suggest it has had an active past. It has few craters on its surface, but it does have long faults that appear to have formed when the icy crust broke, plus large basins that seem to have been flooded repeatedly by liquids from the interior. Even more interesting are the dark smudges visible in the southern polar cap; astronomers have interpreted these as sunlight-darkened deposits of methane that once erupted out of liquid nitrogen geysers.

Rings

Both Uranus and Neptune have ring systems although both are dark and quite faint. Uranus's rings consist of water ice bodies, mixed with methane and other organic compounds, darkened by exposure to radiation, and very little dust. On the other hand, Neptune's rings appear to be composed largely of dust with very few substantive ice chunks. Generally both planets have narrow, well-defined rings only a few kilometres wide, although each system has a few rings that are substantially wider, greater than 1000 km. Along with the great distance to the ice giants the ring dimensions should tell you that it is very difficult to learn much about them. Most of what we do know about them came from the *Voyager 2* flybys and recent Hubble Space Telescope images.

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Exploration

The only spacecraft to visit Uranus (1986) and Neptune (1989) has been *Voyager 2* and both visits were, of course, flyby missions. *Voyager 2* has now crossed the heliopause and entered interstellar space. The flybys discovered new moons and rings of both Uranus and Neptune as well as observing various surface features and measuring magnetic field strengths and weather patterns.

Proposals have been developed to explore further these ice giants but none have yet been approved. It is unlikely that any robotic missions will take place before the late 2020s.

14.5 Dwarf Planets

Beyond Neptune lies the Kuiper belt, a doughnut-shaped region extending from roughly 30 AU to 50 AU. This region consists of billions of icy planetesimals left over from the formation of the solar system. Sizes of these objects vary from small bits of ice and rock to large spheres with rocky cores and icy lithospheres more than 500 km in diameter. The largest of these planetesimals are known as the **dwarf planets**. To date, there are five official dwarf planets, four of which are found in the Kuiper belt, Pluto being the best known. The fifth official dwarf planet, Ceres, lies in the asteroid belt between Mars and Jupiter.

What Defines a Planet?

You might be wondering exactly what dwarf planets are, and how this classification came into being. Prior to 2006 there was no formal definition of "planet." The term originated with Greek astronomers who called star-like objects that moved across the sky *asteres planetai*, meaning wandering stars. Over the years, the word planet was used generally to refer to major objects orbiting the Sun, so when Pluto was discovered in 1930 it was logical to regard it as the ninth planet in our solar system.

To understand why Pluto is no longer considered a planet, you need to know more about the Kuiper belt of small bodies. Since 1992, astronomers have discovered over two thousand icy bodies orbiting beyond Neptune and there may be as many as 100 million objects in the Kuiper belt larger than 1 km in diameter. As telescope technology evolved, larger Kuiper belt objects (KBOs) were discovered. In 2005, Michael Brown and his team discovered Eris, a KBO having about the same diameter as Pluto. Would Eris become the tenth planet? How many other KBOs roughly this size would be found? The IAU quickly stepped in to develop a formal definition of "planet," and in 2006 declared an object is regarded as a planet (a) if it is in orbit around the Sun, (b) if its own gravity is large enough to make it spherical, and (c) if it has "cleared" its neighbourhood of small objects in its orbit. Solar system bodies meeting the first two criteria but not the third were to be classified as dwarf planets. Clearly, Pluto was re-classified as a dwarf planet, along with Eris. Many, including some astronomers, hold a delightful fondness for Pluto but it is very unlikely to be reinstated as a member of the classical planet classification.

Pluto

Pluto is a small, icy world. It is neither Jovian nor Terrestrial. Its orbit is highly inclined to the ecliptic and so elliptical that Pluto actually comes closer to the Sun than Neptune at times. At perihelion it is 29.66 AU from the Sun but its aphelion distance is 49.3 AU, resulting in an eccentricity of 0.249 and an orbital period of 248 years. Its diameter is about 20 percent that of Earth and its mass is less than 1 percent of Earth.

Pluto is very difficult to observe from Earth. It has only 65 percent the diameter of Earth's moon. In Earth-based telescopes it never looks like more than a faint point of light, and even in Hubble Space Telescope images it shows little detail. Orbiting so far from the Sun, Pluto is cold enough to freeze most compounds you think of as gases; Earth-based spectroscopic observations found evidence of nitrogen ice and a thin atmosphere consisting of nitrogen and carbon monoxide with small amounts of methane.

However, our knowledge of Pluto exploded in 2015 when a flyby spacecraft called *New Horizons* passed within 12 500 km of Pluto's surface. Figure 14.13 shows our first ever close-up view of Pluto. The "heart of Pluto" in the lower part of this side of Pluto, measuring about 1600 km across, is a nitrogen glacier known as Sputnik Planitia. The lack of craters in this glacier tells you that this huge area must renew itself continuously despite its cold 40 K temperature.

New Horizons also made some interesting discoveries about Pluto's atmosphere (see Figure 14.14). Consisting of mostly nitrogen with traces of methane and carbon monoxide the surface pressure is about 10 μbar (that's about 100 000 times less than Earth's surface pressure). In addition, it seems that the atmosphere extends up to 1500 km above Pluto's surface. Because of the relatively high eccentricity of Pluto's orbit, prior to the 2015 flyby it was thought that Pluto's atmosphere dwindled to almost nothing around its

dwarf planet A body that orbits the Sun, is not a satellite of a planet, is massive enough to pull itself into a spherical shape, but is not massive enough to clear out other bodies in and near its orbit—for example, Pluto, Eris, and Ceres.

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NASA/JHUAPL/SwRI

Figure 14.13 Global Mosaic of Pluto in True Colour. This global view of Pluto taken by NASA's *New Horizons* spacecraft instruments show features as small as 2 km. This view clearly shows the large, heart-shaped plain, measuring about 1600 km across, surrounded by cratered terrains, canyons, and mountain ranges similar to those found on Mars and Europa.



NASA, JHU's APL, SwRI; Color Processing: Thomas Appéré

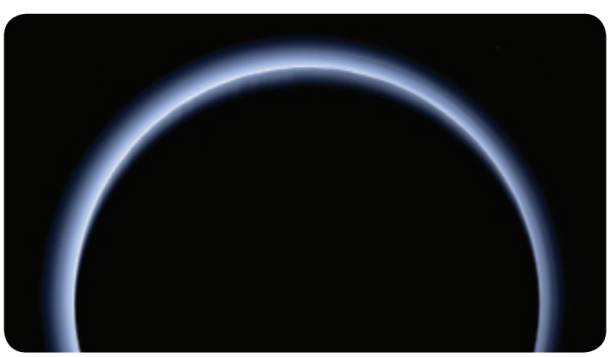
Figure 14.14 MU_{69} (Ultima Thule) photographed by NASA's *New Horizons* on January 1, 2019. This is the farthest object ever explored and photographed by any spacecraft.

aphelion. However, the *New Horizons* measurements of a much lower atmospheric escape rate than previously predicted now suggest no such atmospheric loss during Pluto's entire 248-year journey around the Sun. The data from *New Horizons* will take years of study and more surprises (and puzzles) will surely be revealed. *New Horizons* has now moved further into the Kuiper belt, and completed a planned flyby of KBO MU_{69} on January 1, 2019. MU_{69} is now known as Ultima Thule—having a snowman appearance although it is, in fact, a contact binary with two lobes (the "snowman" body and head) connected by a bright, narrow neck. The two roughly spherical lobes were probably two separate objects initially that slowly merged together resulting in a 32-km-long KBO (Figure 14.15).

To date, five moons of Pluto have been discovered (Figure 14.16). Four of them are quite small, but the largest, Charon, has half the diameter of Pluto but only 12 percent of its mass. Charon orbits Pluto with a period of 6.4 days in the same plane as the other moons, and the orbit is highly inclined to the ecliptic. You should keep in mind that Pluto and Charon actually orbit about their barycentre, which is just outside Pluto's surface. Pluto and Charon are tidally locked facing each other with Pluto's "heart" on its outside face. Knowing the diameters and masses of Pluto and Charon allows astronomers to calculate that their densities are both about 2 g/cm^3. This indicates that Pluto and Charon must each contain about 35 percent ice and 65 percent rock.

Ceres

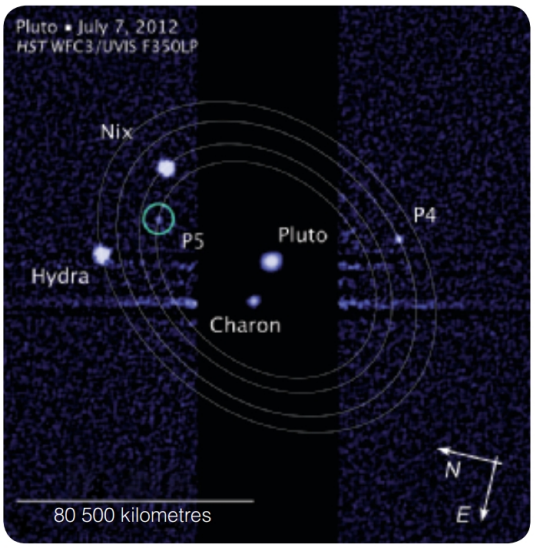
Ceres, the only dwarf planet not found in the Kuiper belt, resides in the main asteroid belt between Mars and Jupiter. By far the largest asteroid, Ceres contains about a third of the total mass of this belt of rocky bodies. Giuseppe Piazzi discovered Ceres on the first day of the 19th century: January 1, 1801. A day on Ceres lasts 9 hours, but it



NASA/Johns Hopkins University Applied Physics Laboratory/ Southwest Research Institute

Figure 14.15 A near-true-colour image taken by *New Horizons* after its flyby. Numerous layers of blue haze float in Pluto's atmosphere.

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NASA; ESA; M. Showalter, SETI Institute

Figure 14.16 Hubble image of all five known moons of Pluto, with estimated orbits for the outer satellites. The brightness of Pluto and Charon is damped to bring out the dimmer moons.

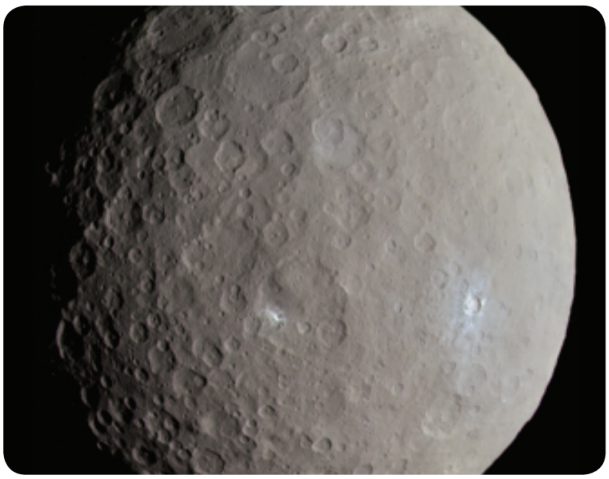
has an orbital period of 4.6 years. It has a mean radius of 473 km but a mass of just 1.3 percent of Earth's moon, so its density is about 2 g/cm^3, the same as Pluto and Charon.

NASA's *Dawn* spacecraft began orbiting Ceres in March 2015 and sent back high-resolution pictures of the dwarf planet showing a heavily cratered surface (Figure 14.17). Numerous bright spots have been observed by *Dawn* leading to much speculation about their origin and composition. Measurements using near-infrared spectroscopy suggest these spots contain large amounts of sodium bicarbonate most likely of subsurface origin.

Recent analyses suggest that between Ceres's thin outer crust and rocky core lies a thick water ice layer possibly containing more water than all the fresh water on Earth. Data from *Dawn* confirm Ceres's tenuous atmosphere, consisting mostly of water vapour, and indicate that it is probably connected to solar activity as ice within craters sublimates when struck by solar wind particles.

Other Dwarf Planets

The remaining three dwarf planets recognized by the IAU are Eris (mentioned previously), Haumea, and Makemake. Other candidates are known to exist (Sedna, Quaoar, and Orcus, for example) but have yet to be confirmed by the IAU. What this indicates is that the Kuiper belt may be teeming with objects massive enough to be in hydrostatic equilibrium and therefore largely spherical. It is, however, unlikely that they would outnumber the countless small, irregularly shaped bodies that constitute the Kuiper belt.



NASA/JPL-Caltech/UCLA/MPS/DLR/IDA/Justin Cowart

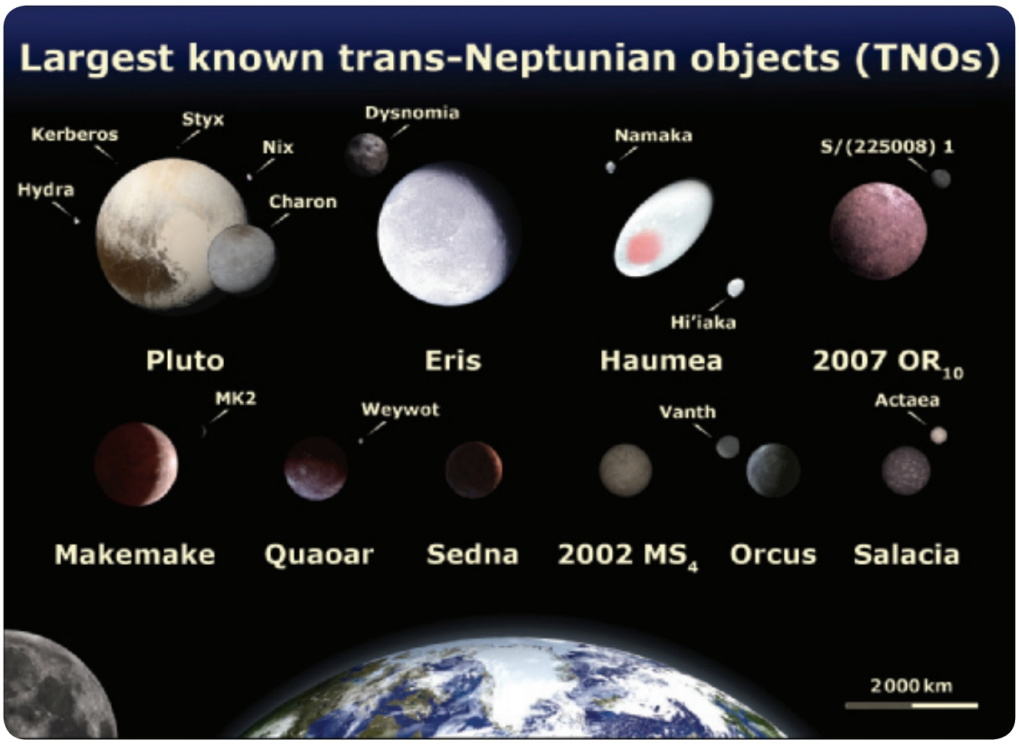
Figure 14.17 Ceres image taken by the *Dawn* spacecraft. Notice the two bright spots in crater floors.

Although Eris is the most massive of the five dwarf planets it is not the largest, having a mean radius just 25 km smaller than Pluto, although its density is 36 percent greater than Pluto's. This tells you that the composition and internal structure of Eris is quite different from Pluto, and probably consists mainly of rocky materials whereas Pluto likely consists of a rocky core surrounded by a water ice mantle. The orbit of Eris is highly eccentric, having an aphelion distance of almost 100 AU and a perihelion distance of just under 40 AU—resulting in an eccentricity of 0.44 (Pluto's is 0.25) and an inclination of 43.9°. Its orbital period is 557 years. Eris has one known moon, Dysnomia.

Haumea and Makemake have similar orbital characteristics, with periods around 300 years and eccentricities of about 0.2. Haumea has an unusual ellipsoidal shape, with a major axis about twice as long as its minor axis (Figure 14.18). This shape may have resulted from a giant collision with another trans-Neptunian object, which left Haumea as the largest remaining object along with its two captured moons. Remarkably, Haumea has a thin ring about 70 km wide and is now the fifth known ringed solar system object.

Makemake is distinctly spherical, with one known moon nicknamed MK2. Currently 52.3 AU from the Sun, Makemake is nearing its aphelion position. In spite of this distance, it is the second brightest KBO (visually) after Pluto. Both the Spitzer Space Telescope and the Herschel Space Telescope have been used to determine that Makemake has an absolute visual magnitude of –0.44 that, when combined with its estimated diameter of about 1500 km and high albedo, suggests a surface temperature of about 35 K: bright but cold.

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Figure 14.18 Largest known trans-Neptunian objects (TNOs).

The **Big Picture**

What Are We? Trapped?

The farthest anyone has been from Earth is the Moon. We have sent robotic spacecraft to visit most of the larger worlds in our solar system, and we have found them strange and wonderful places, but no human has ever set foot on any of them. It appears we are trapped on Earth.

In the first episode of the television series *Cosmos*, Carl Sagan states, "the surface of the Earth is the shore of the cosmic ocean and recently we've waded a little way out, maybe ankle-deep, and the water seems inviting." By then, in the late 1970s, humans had set foot on the Moon reflecting on our ability to leave our planetary home but not for any extended time. Getting away from Earth's gravitational field is difficult and calls for very large rockets. The United States built such rockets in the 1960s and early 1970s, but such rockets are no longer in production. Today's rocket technology can carry astronauts just a few hundred kilometres above Earth's surface to the International Space Station (see the cover of this book). Some privately funded companies are starting to emerge (SpaceX, Blue Origin, etc.) and show great promise. Some nations, including the United States and Russia, have plans to send humans back to the Moon and eventually to Mars but the budgets required for such human exploration are significant. Does Earth's civilization have the resources to fulfill these intentions? Only time will tell.

Furthermore, we Earthlings have evolved to fit the environment on Earth. None of the planets or moons you explored in this chapter would welcome you. Lack of air and extreme heat or cold are obvious problems, but also Earthlings have evolved to live with Earth's gravity. Astronauts in space for just a few weeks suffer biomedical problems because they are no longer in Earth's gravity. Living in a colony on Mars or the Moon might raise similar problems. Just getting to the outer planets would take decades of space travel; living for years in a colony on one of the Jovian moons under low gravity and exposed to the planet's radiation belts may be beyond the capability of the human body. We may be trapped on Earth not because we lack the technology but because we need Earth's protection.

The human race is changing the world we live on at a frantic pace, and it appears that many of those changes

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could make Earth less hospitable to human life. But where would we go? At this point in our history it is apparent that there is no better place. All of our exploring of unearthly worlds serves to remind us of the nurturing beauty of our home planet. We must work harder and more intelligently to protect Earth.

Review and Discussion Questions

Review Questions

1. Why is Jupiter so much richer in hydrogen and helium than Earth?
2. How can Jupiter have a liquid interior and not have a definite liquid surface?
3. How does the dynamo effect account for the magnetic fields of Jupiter, Saturn, Uranus, and Neptune?
4. Why are the belts and zones on Saturn less distinct than those on Jupiter?
5. Why do astronomers conclude that none of the Jovian planets' rings can be left over from the formation of the planets?
6. How can a moon produce a gap in a planetary ring system?
7. Explain why the amount of geological activity on Jupiter's moons varies with distance from the planet.
8. What makes Saturn's F ring and the rings of Uranus and Neptune so narrow?
9. Why is the atmospheric activity of Uranus less than that of Saturn and Neptune?
10. Why do astronomers suspect that Saturn's moon Enceladus is geologically active?
11. What are seasons like on Uranus?
12. Why are Uranus and Neptune respectively green-blue and blue?
13. What evidence is there that Neptune's moon Triton has been geologically active recently?
14. What evidence indicates that catastrophic impacts have occurred in the solar system's past?
15. **How Do We Know?** Why would you expect research in archaeology to be less well funded than research in chemistry?

Discussion Questions

1. Some astronomers argue that Jupiter and Saturn are unusual, while other astronomers argue that all planetary systems should contain one or two such giant planets. What do you think? Support your argument with evidence.
2. Why don't the Terrestrial planets have rings? If you were to search for a ring among the Terrestrial planets, where would you look first?

Learning to Look

1. This photo shows a segment of the surface of Jupiter's moon Callisto. Why is the surface mostly dark? Why are some craters dark and some white? What does this image tell you about the history of Callisto?



NASA/JPL/University of Arizona

2. The *Cassini* spacecraft recorded this photo of Saturn's A ring and Encke's division. What do you see in this photo that tells you about processes that confine and shape planetary rings?



NASA/JPL/Space Science Institute

3. Two images are shown here of Uranus's northern hemisphere: one as it would look to the eye, and the other through a red filter that enhances methane clouds. What do the atmospheric features tell you about circulation on Uranus?



NASA/JPL/STScI

STUDY TOOLS

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PART FIVE

15 Life on Other Worlds



ESO/L. Calçada

CHAPTER OUTLINE

15.1 The Nature of Life
15.2 Life in the Universe
15.3 Intelligent Life in the Universe

GUIDEPOST

Astronomy is the study not only of the physical universe but also of your role as a living being in the evolution of the universe. Everything you have learned so far from this book has been preparation for this final chapter.

As you read this chapter, you will encounter four important questions:

- What is life?
- How did life originate on Earth?
- Does life exist on other worlds?
- Can humans communicate with intelligent beings on other worlds?

These are questions astronomers and biologists are still striving to answer, and where there are still lots of opportunities for new discoveries.

The study of life in the cosmos is one of the most vital areas of astronomy. It challenges us to think about ourselves from another perspective, not as the centre of the universe, but perhaps only as one of billions of species that populate it.

When the universe began, the atoms of carbon, oxygen, and other heavy elements that make up your body didn't exist. They were produced and scattered into the universe by generations of stars. Through processes we are only just beginning to understand, some of those elements transformed from mere inanimate matter into living beings. Some of these living beings include conscious entities such as yourself, and perhaps alien intelligences on other planets. Through you and your

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The universe is a pretty big place. If it's just us, seems like an awful waste of space.

Carl Sagan,
astronomer and author of Contact

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astrobiology The study of the origin and evolution of life on Earth and the possibility of life on other worlds.

investigations, the universe can know itself.

A whole new branch of science called **astrobiology** has developed to probe questions about the origin and development of life in the cosmos. We'll explore it in this chapter.

15.1 The Nature of Life

What is life? Philosophers have struggled with this question for thousands of years without reaching a consensus. Although we may not be able to place a clear dividing line between "life" and "not life," we can arrive at a good working definition by considering the characteristics common to all life on Earth. On Earth, all life extracts energy from its surroundings, maintains itself, modifies its surroundings to foster its own survival, reproduces, and evolves by the process of natural selection. The NASA astrobiology program uses an even simpler working definition; namely, that life is "a self-sustaining chemical system capable of Darwinian evolution." What kind of chemical system?

The Physical Basis of Life

The processes of life are complex and demand an equally complex mechanism for storing and transmitting information. The physical basis of life on Earth is the element carbon. Each carbon atom can bond with four other atoms, so carbon can form long, complex, stable chains that are capable of storing a lot of information. Contrast carbon with hydrogen: hydrogen can only bond with one other atom at a time, making it impossible to base complex molecules on hydrogen.

While all life on Earth is based on carbon, other elements may serve the same purpose elsewhere in the universe. Silicon is also a highly abundant element that can bond to four other atoms at a time. Science fiction authors have often speculated about silicon-based life. Even stranger life forms have been proposed, based on electromagnetic fields and ionized gas. These hypothetical life forms make for fascinating speculation, but they can't be studied as systematically as carbon-based life, simply because we have not found any of them yet. This chapter is concerned with the origin and evolution of life as it is on Earth, based on carbon, not because of lack of imagination but because it is the only form of life about which we know anything.

The chemical building blocks of life, such as the elements carbon, nitrogen, oxygen, and phosphorus, are produced in stars and scattered into the interstellar medium by stellar winds and supernovae. Nonbiological processes then convert these simple atoms into some of the basic building blocks of life, such as amino acids for making proteins. As Carl Sagan explained in his masterpiece book *Cosmos*: "The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of star stuff."*

Carbon-based life has its mysteries. What makes a lump of carbon-based molecules a living thing? An important part of the answer lies in the transmission of information from one molecule to another.

Information Storage and Duplication

Almost every action performed by a living cell is carried out by the chemicals it manufactures. Cells must store recipes for all these chemicals, use them when they need them, and pass them on to their offspring.

Study **Visualizing Astronomy 15.1, DNA: The Code of Life**, and notice three important points:

1. The chemical recipes of life are stored in each cell as information on DNA molecules, which resemble a ladder with rungs that are composed of chemical bases. The recipe information is expressed by the sequence of ladder rungs, providing instructions that guide chemical reactions within the cell.
2. DNA instructions normally are expressed by being copied into a messenger molecule called RNA, which causes molecular units called amino acids to become connected into large molecules called proteins. Proteins serve as the cell's basic structural molecules or as enzymes that control chemical reactions.
3. The instructions stored in DNA are genetic information passed along to offspring. The DNA molecule reproduces itself when a cell divides so that each new cell contains a copy of the original information.

To produce viable offspring, a cell must be able to make copies of its DNA. Surprisingly, it is important for the continued existence of all life that not all the copies be exact duplicates.

*Carl Sagan, 1980, Cosmos, Random House, page 233.

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Modifying the Information

Earth's environment changes continuously. To survive, species must change as their food supply, climate, or home terrain changes. If the information stored in DNA could not change, life would quickly go extinct. The process by which life adjusts itself to its changing environment is called **biological evolution**.

When an organism reproduces, its offspring receives a copy of its DNA. Sometimes external effects such as radiation alter the DNA during the parent organism's lifetime, and sometimes mistakes occur in the copying process, so that occasionally the copy is slightly different from the original. These altered sections of DNA are called mutations. Some mutations are fatal, killing the afflicted organisms before they can reproduce. However, in rare but vitally important cases, a mutation can actually help an organism survive.

These changes produce variation among the members of a species. All of the squirrels in the park may look the same, but they carry a range of genetic variation. Some may have slightly longer tails or faster-growing claws. These variations make almost no difference until the environment changes. For example, if the environment becomes colder, squirrels with a heavier coat of fur will, on average, survive longer and produce more offspring than squirrels with shorter fur. Likewise, the offspring that inherit this beneficial variation will also live longer and have more offspring of their own. These differing rates of survival and reproduction are examples of **natural selection**. Over time, the beneficial variation becomes more common, and a species can evolve until the entire population shares the trait. In this way, natural selection adapts species to their changing environments by selecting, from the huge array of random variations, those that would most benefit the survival of the species.

It is commonly believed that evolution is random, but that is not true. Individual mutations may be random, but environmental pressures drive change in particular directions.

15.2 Life in the Universe

The billions of chemical bases that make up human DNA did not just come together in the right order by chance. It has taken billions of years of changing environmental conditions and natural selection to bring life on Earth to its current state of complexity and specialization. We can read the history of those changes in the fossil record and in the genetic codes of the most ancient living organisms. For example, we can see that the earliest organisms on Earth were far simpler than most of the organisms that exist today. At the very beginning, life may have consisted of nothing more than carbon-chain molecules that could copy themselves. What evidence exists for this hypothesis?

biological evolution The processes of mutation, variation, and natural selection by which life adjusts itself to its changing environment.

natural selection The process by which genetic traits that confer advantages to survival or reproduction are preserved, gradually altering organisms to suit their environments.

stromatolite A layered formation caused by mats of algae or bacteria combined with sediments.

The Origin of Life on Earth

The oldest fossils are those of marine organisms, which suggests that life began in the ocean. These ancient fossils are not easy to recognize because the earliest living things contained no easily preserved hard parts like bones or shells, and because the individual organisms were microscopic. Some rocks from Western Australia that are more than 3.4 billion years old contain features that experts identify as fossil **stromatolites**: mineralized layers built up from deposits of single-celled organisms that lived in shallow water long ago (Figure 15.1). This evidence indicates that simple organisms lived in Earth's oceans 3.4 billion or more years ago, less than 1.2 billion years after Earth formed. Where did these simple organisms come from?

Greek philosophers Democritus, Plato, and Aristotle suggested that life appeared spontaneously out of non-life wherever conditions were appropriate. Charles Darwin wrote in 1871 about the possibility that life originated in a



Dirk Wiersma/Science Source

Figure 15.1 Cross-section of layers in a fossilized stromatolite. Layers are made of mineralized mats of bacteria covered repeatedly by sediment. Fossilized stromatolites have been found within rocks more than 3.4 billion years old. This sample measures 30 centimetres across.

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Visualizing Astronomy 15.1

DNA: THE CODE OF LIFE

1

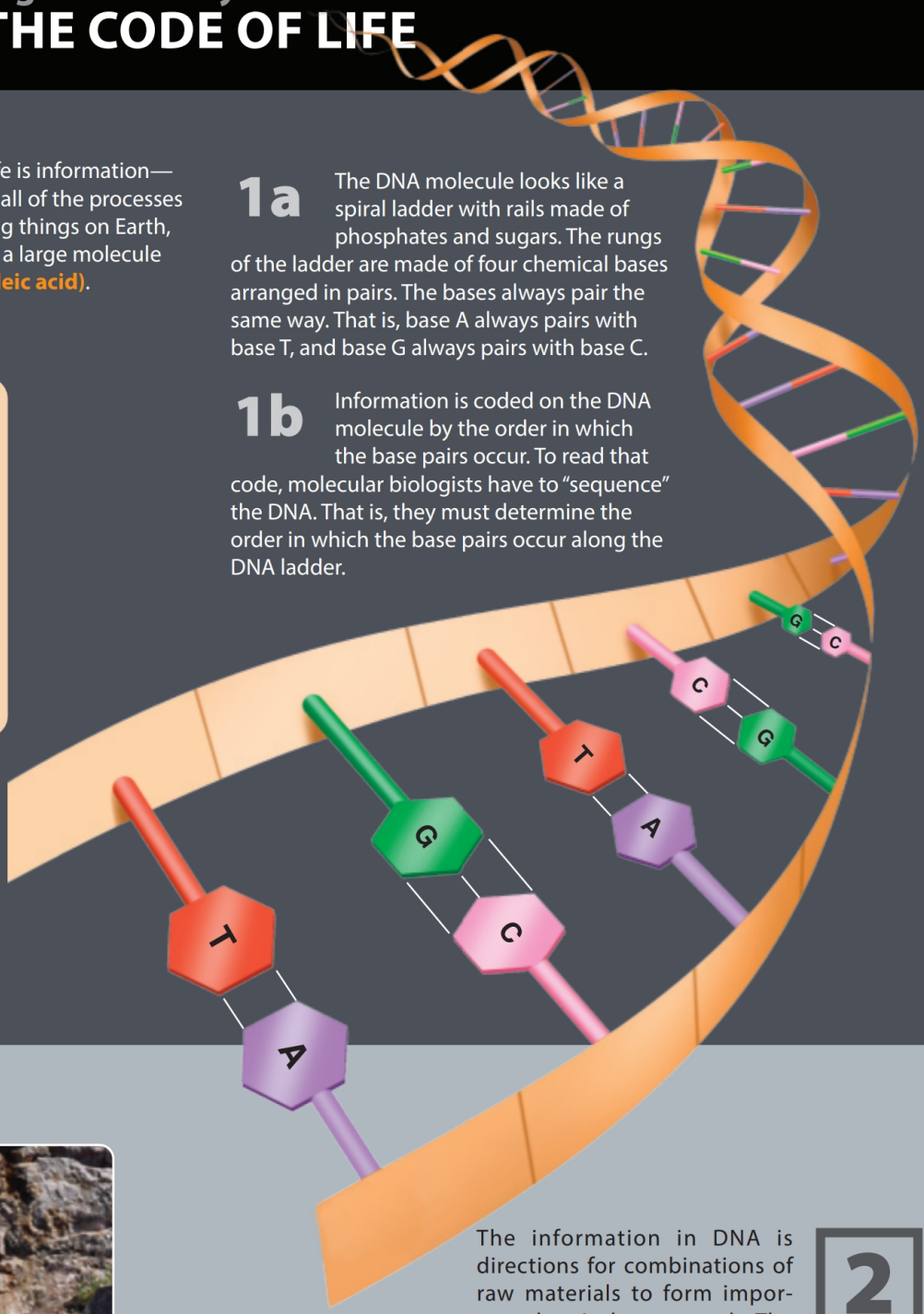
The key to understanding life is information—the information that guides all of the processes in an organism. In most living things on Earth, that information is stored in a large molecule called **DNA (deoxyribonucleic acid)**.

1a The DNA molecule looks like a spiral ladder with rails made of phosphates and sugars. The rungs of the ladder are made of four chemical bases arranged in pairs. The bases always pair the same way. That is, base A always pairs with base T, and base G always pairs with base C.

1b Information is coded on the DNA molecule by the order in which the base pairs occur. To read that code, molecular biologists have to "sequence" the DNA. That is, they must determine the order in which the base pairs occur along the DNA ladder.

The Four Bases

- A — Adenine
- C — Cytosine
- G — Guanine
- T — Thymine



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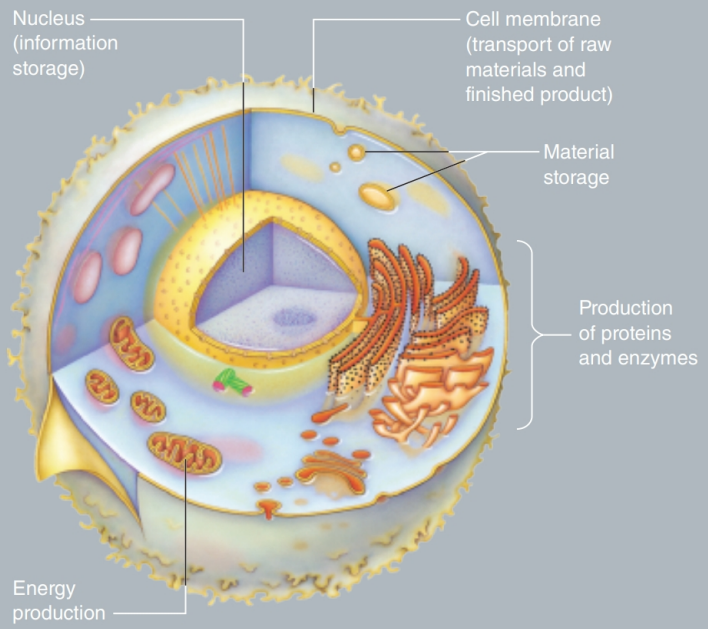
Vesna Milosevic-Zdjelar

The traits you inherit from your parents, the chemical processes that animate you, and the structure of your body are all encoded in your DNA. When people say, "You have your mother's eyes," they are talking about DNA codes.

2

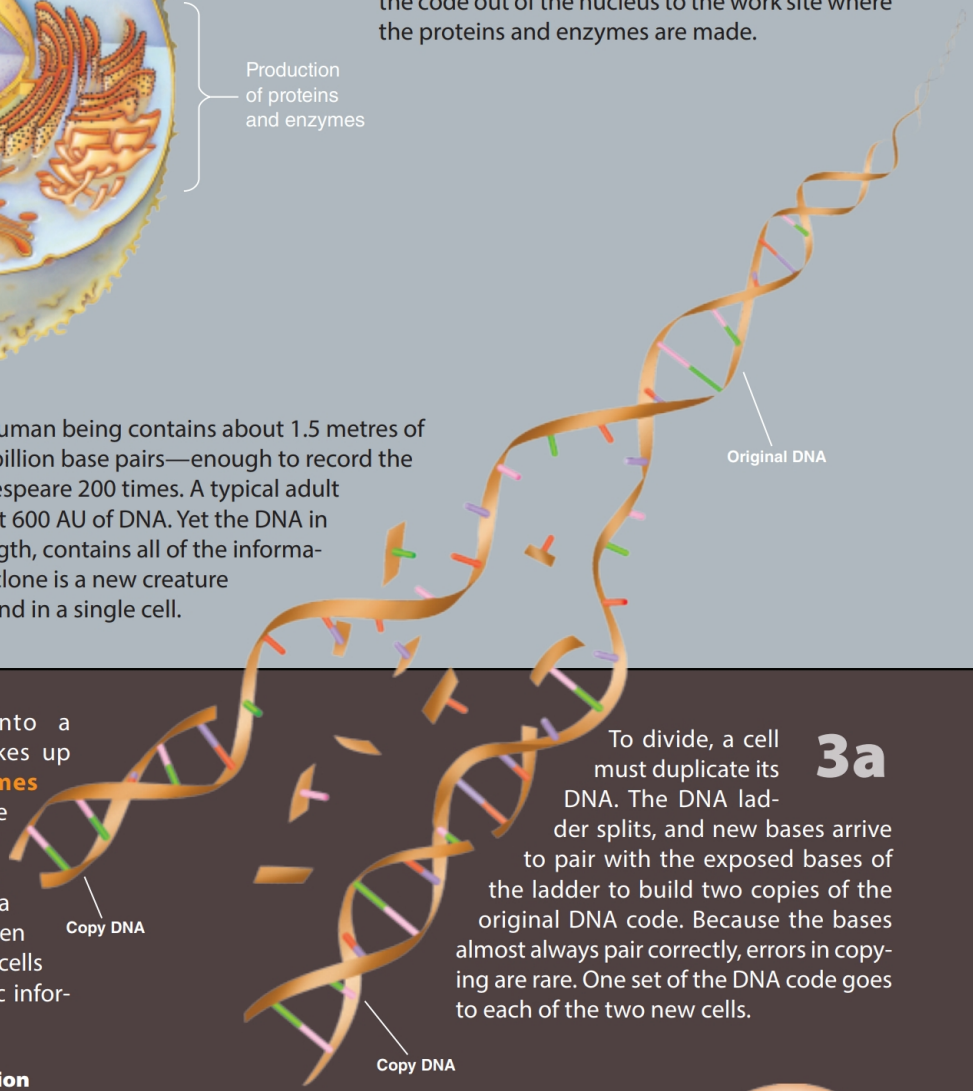
The information in DNA is directions for combinations of raw materials to form important chemical compounds. The building blocks of these compounds are relatively simple **amino acids**. Segments of DNA act as templates that guide the amino acids to join together in the correct order to build specific **proteins**, chemical compounds important to the structure and function of organisms. Some proteins called **enzymes** regulate chemical processes. In this way, DNA recipes regulate the production of the compounds of life.

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2a A cell is a tiny factory that uses the information encoded in DNA to produce molecules. Most of the DNA remains safe in the nucleus of a cell, and the code is copied to create a strand of **RNA (ribonucleic acid)**. Like a messenger carrying blueprints, the RNA carries the code out of the nucleus to the work site where the proteins and enzymes are made.

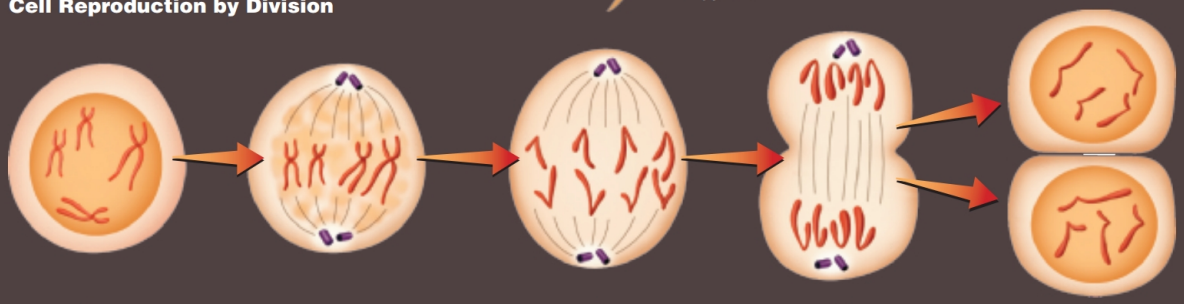
2b A single cell from a human being contains about 1.5 metres of DNA with about 4.5 billion base pairs—enough to record the entire works of Shakespeare 200 times. A typical adult human contains a total of about 600 AU of DNA. Yet the DNA in each cell, only 1.5 metres in length, contains all of the information to create a new human. A clone is a new creature created from the DNA code found in a single cell.



3 DNA, coiled into a tight spiral, makes up the **chromosomes** that contain the genetic material in a cell. A **gene** is a segment of a chromosome that controls a certain product or function. When a cell divides, each of the new cells receives a copy of the genetic information in the chromosomes.

3a To divide, a cell must duplicate its DNA. The DNA ladder splits, and new bases arrive to pair with the exposed bases of the ladder to build two copies of the original DNA code. Because the bases almost always pair correctly, errors in copying are rare. One set of the DNA code goes to each of the two new cells.

Cell Reproduction by Division



a As a cell begins to divide, its DNA duplicates itself.

b The duplicated chromosomes move to the middle.

c The two sets of chromosomes separate, and . . .

d the cell divides to produce . . .

e two cells, each containing a full set of the DNA code.

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"warm little pond" from inorganic matter such as ammonia, phosphoric salts, light, heat, electricity. In the 1920s, Russian chemist Alexander Oparin and English geneticist John Haldane independently suggested that life may have arisen from simple organic chemicals that were themselves formed through purely non-biological processes. Oparin speculated that in Earth's primitive ocean, these chemicals reacted with one another to form more complex compounds such as proteins, and "were finally transformed into primary living beings—the forebears of all life on Earth." Today, we call this process **abiogenesis**. The first experimental evidence for abiogenesis didn't arrive until the 1950s and many parts of the process remain mysterious today.

An important experiment performed by Stanley Miller and Harold Urey in 1952 sought to recreate the conditions in which life on Earth began. The **Miller-Urey experiment** consisted of a sterile, sealed glass container holding water, hydrogen, ammonia, and methane. These chemicals were chosen to simulate the atmosphere of the young Earth. An electric arc inside the apparatus created sparks to simulate the effects of lightning in Earth's early atmosphere (Figure 15.2).

Miller and Urey let the experiment run for a week and then analyzed the material inside. They found that the interaction between the electric arc and the simulated atmosphere produced many organic molecules from the raw material of the experiment, including such important building blocks of life as amino acids. When other scientists later ran the experiment using different energy sources, such as hot silica to represent molten lava spilling into the ocean, similar molecules were produced. Even the amount of UV radiation present in sunlight is sufficient to produce complex organic molecules.

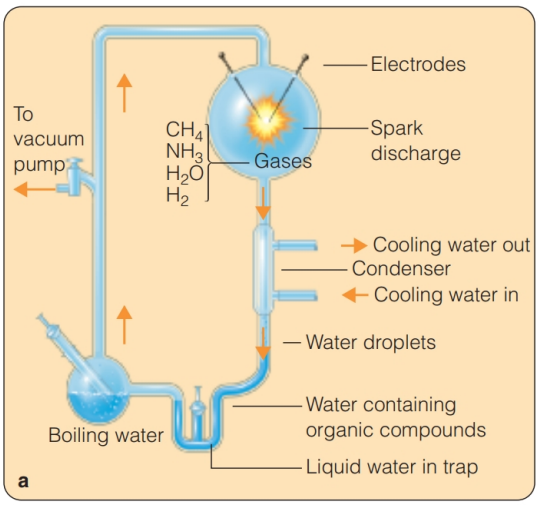
According to updated models of the formation of the solar system and Earth (see Chapters 12 and 13), Earth's early atmosphere probably consisted mostly of carbon dioxide, nitrogen, and water vapour instead of the mix of hydrogen, ammonia, and methane assumed by Miller and Urey. When gases corresponding to the newer understanding of the early Earth atmosphere are processed in a Miller apparatus, lower but still significant numbers of organic molecules are created.

The Miller-Urey experiment is important because it shows that complex organic molecules form naturally in a wide variety of circumstances.

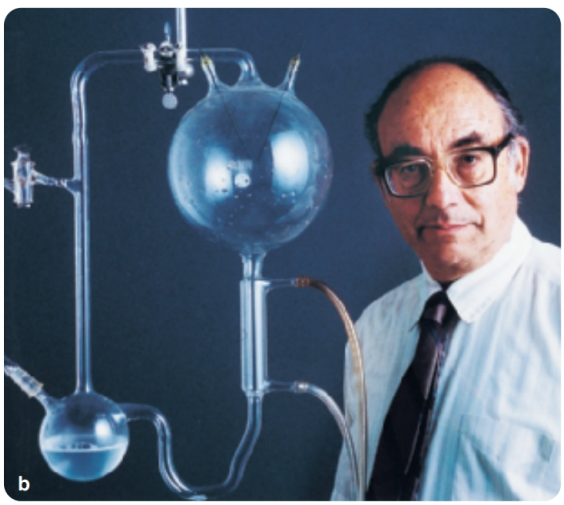
abiogenesis The process by which life forms from non-living components.

Miller-Urey experiment An experiment that attempted to reproduce early Earth conditions and showed how easily amino acids and other organic compounds can form from non-biological ingredients.

primordial soup The rich solution of organic molecules in Earth's first oceans.



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Courtesy the Estate of Stanley Miller

Figure 15.2 (a) The Miller-Urey experiment circulated gases through water in the presence of an electric arc. This simulation of primitive conditions on Earth produced many complex organic molecules, including amino acids, the building blocks of proteins. (b) Stanley Miller with the Miller-Urey apparatus.

Lightning, sunlight, and hot lava pouring into the oceans are just some of the energy sources that can naturally rearrange simple common molecules into the complex molecules that make life possible. If you could travel back in time, you would expect to find Earth's first oceans filled with a rich mixture of organic compounds, the **primordial soup**.

Many of the organic compounds in the primordial soup would have been able to link up to form larger molecules. Amino acids, for example, can link together to form proteins by joining ends and releasing a water molecule (Figure 15.3). It was initially thought that this must have occurred in Sun-warmed tidal pools where organic molecules were concentrated by evaporation. However,

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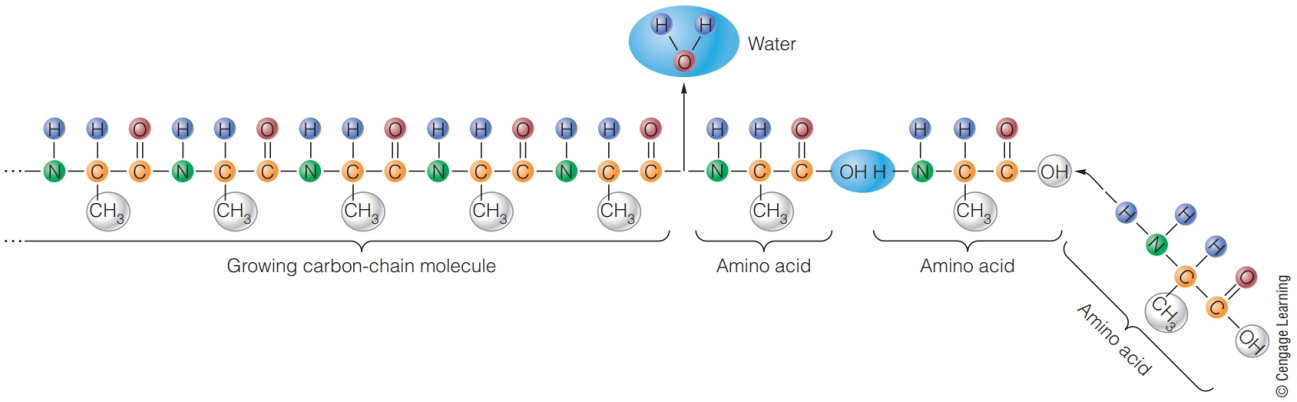


Figure 15.3 Amino acids can link together by releasing a water molecule to form long carbon-chain protein molecules. The amino acid in this hypothetical example is alanine, one of the simplest.

violent episodes of volcanism and catastrophic meteorite impacts would probably have destroyed complex molecules developing at the surface, so scientists now think that successful linkage of complex molecules might have taken place in the deep ocean, perhaps near the hydrothermal vents at mid-ocean rises (refer to **Visualizing Astronomy 13.1, The Active Earth**, and Figure 15.8).

These complex organic molecules were still not living things. Even though some proteins may have contained hundreds of amino acids, they did not reproduce; rather, they linked and broke apart at random. Because some molecules are more stable than others, and some bond together more easily than others, scientists hypothesize that a process of chemical evolution eventually concentrated the various smaller molecules into the most stable, larger forms. Eventually, according to this hypothesis, somewhere in the oceans, after sufficient time, a molecule formed that could copy itself. At that point, the chemical evolution of molecules became the biological evolution of living things.

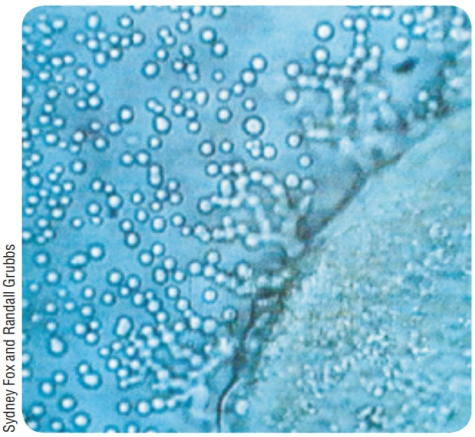
The Miller-Urey experiment demonstrated that complex chemical precursors to life could have formed on the young Earth. Today, we know that many of the chemical precursors of life already exist in the interstellar medium and may have been incorporated into the young Earth when it formed, or delivered to it by asteroids and comets later on. So there is little doubt that the young Earth possessed a wide variety of complex chemicals. However, neither the Miller-Urey experiment nor many similar experiments that have followed have succeeded in producing life from non-living chemicals. There are many steps in the transition from chemicals to biology that remain poorly understood. How did the first cell membranes form, dividing life from its environment? How did life begin to metabolize? Answering these questions has proven very difficult because most of the evidence has long been destroyed by geological processes.

The relatively rapid appearance of life on Earth and the presence of precursor molecules in space has given rise to an alternative theory for life's origin. Perhaps life first developed on another planet and hitchhiked to Earth on fragments of rock that were blasted into space by asteroid impacts. We know that fragments of Mars reach Earth regularly, and that some organisms might be hardy enough to survive the journey. It may even be possible that life formed in interstellar space and was delivered to Earth inside meteorites, such as the Murchison meteorite (Figure 15.4). The hypothesis that life spreads through the



Figure 15.4 A piece of the Murchison meteorite. This piece of carbonaceous chondrite fell near Murchison, Australia, in 1969. Analysis of the interior of the meteorite reveals the presence of amino acids. Whether the first chemical building blocks of life on Earth originated in space is a matter of debate, but the amino acids found in meteorites illustrate how commonly amino acids and other complex organic molecules occur in the universe, even in the absence of living things.

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Sydney Fox and Randall Grubbs

Figure 15.5 Single amino acids can be assembled into long protein-like molecules. When such material cools in water, it can form spheres with double-layered boundaries similar to cell membranes. These spheres may have been an intermediate stage in the evolution of life from complex molecules to living cells that have molecules capable of reproducing genetic information.

cosmos on meteorites and space dust is called panspermia (*pan* in Greek means "all" and *sperma* means "seed"). Even if panspermia turns out not to be the source of life on Earth, it may still be responsible for carrying life from planet to planet elsewhere in the cosmos.

The exact process by which the first cells developed is unknown. Experiments have shown that lipids and proteins suspended in water can spontaneously form microscopic spheres the size of cells (see Figure 15.5). Perhaps this is how the first cell membranes formed. It seems certain that the first reproducing molecule to surround itself with a protective membrane must have gained an important survival advantage.

The first cells must have been simple, single-celled organisms much like modern bacteria. Over the course of eons, the natural processes of evolution gave rise to stunningly complex **multicellular** life forms with widely differing ways of life. A common misconception is that life is too complex to have evolved from such simple beginnings. However, it was possible because small variations accumulate, even though that accumulation requires huge amounts of time.

multicellular Comprising more than one cell.

Cambrian explosion A geologically brief period about 540 million years ago during which fossil evidence indicates life on Earth became complex and diverse.

Deep Time and the Evolution of Life

Life has existed on Earth for at least 3.4 billion years, but there is little evidence of anything more than simple organisms until about 560 million years ago, during the Ediacaran period. The few fossils that remain from this period show an increase in the complexity of life forms, from simple multicellular forms to complex combinations of tubes, discs, and "quilts." These Ediacaran organisms were soon supplanted in one of the most important events in biological history: the **Cambrian explosion**. Taking place around 540 million years ago, this sudden, exponential increase in the diversity and complexity of life forms marks the beginning of the Cambrian period and the appearance of large, multicellular life forms as we know them today. The Cambrian explosion is so important to the history of life on Earth that the approximately 4 billion years of Earth history that came before it are often lumped into the category "Precambrian."

When the entire history of Earth is represented on a timeline as shown at the left of Figure 15.6, the Cambrian explosion appears very close to the present. The period when most of today's familiar animals emerged, including fishes, amphibians, reptiles, birds, and mammals, is crammed into a small fraction of Earth's history, since the Cambrian explosion.

When this portion of the diagram is magnified, as shown on the right side of Figure 15.6, you can get a better idea of when these events occurred in the history of life. Humanoid creatures have walked the Earth for about 4 million years. This is a long time compared to a human life, but it represents only the most recent 0.1 percent of Earth's history. All of recorded human history is compressed into a microscopically thin line at the very end of the timeline.

To understand just how thin that line is, imagine the 4.6-billion-year history of Earth as a year-long video that you begin watching on January 1. It would be a very boring video for a very long time. You'd have to watch until March or April before you saw any signs of life. Not until mid-November would you see the emergence of diverse, complex life following the Cambrian explosion. Life wouldn't crawl out of the oceans and onto land until around November 28. A few days later, that life would achieve astonishing complexity. By December 12 the dinosaurs would be walking the continents, and by December 28 they would be gone, leaving mammals and birds to dominate. The first humanoid forms might have appeared by suppertime on New Year's Eve, and by late evening humans would make the first stone tools. From then on, all of human history would happen at lightning speed.

By imagining all of Earth's history compressed into a year, you gain a sense of "deep time." You can appreciate that, for most of the history of our planet, it hosted only comparatively simple forms of life. It took billions

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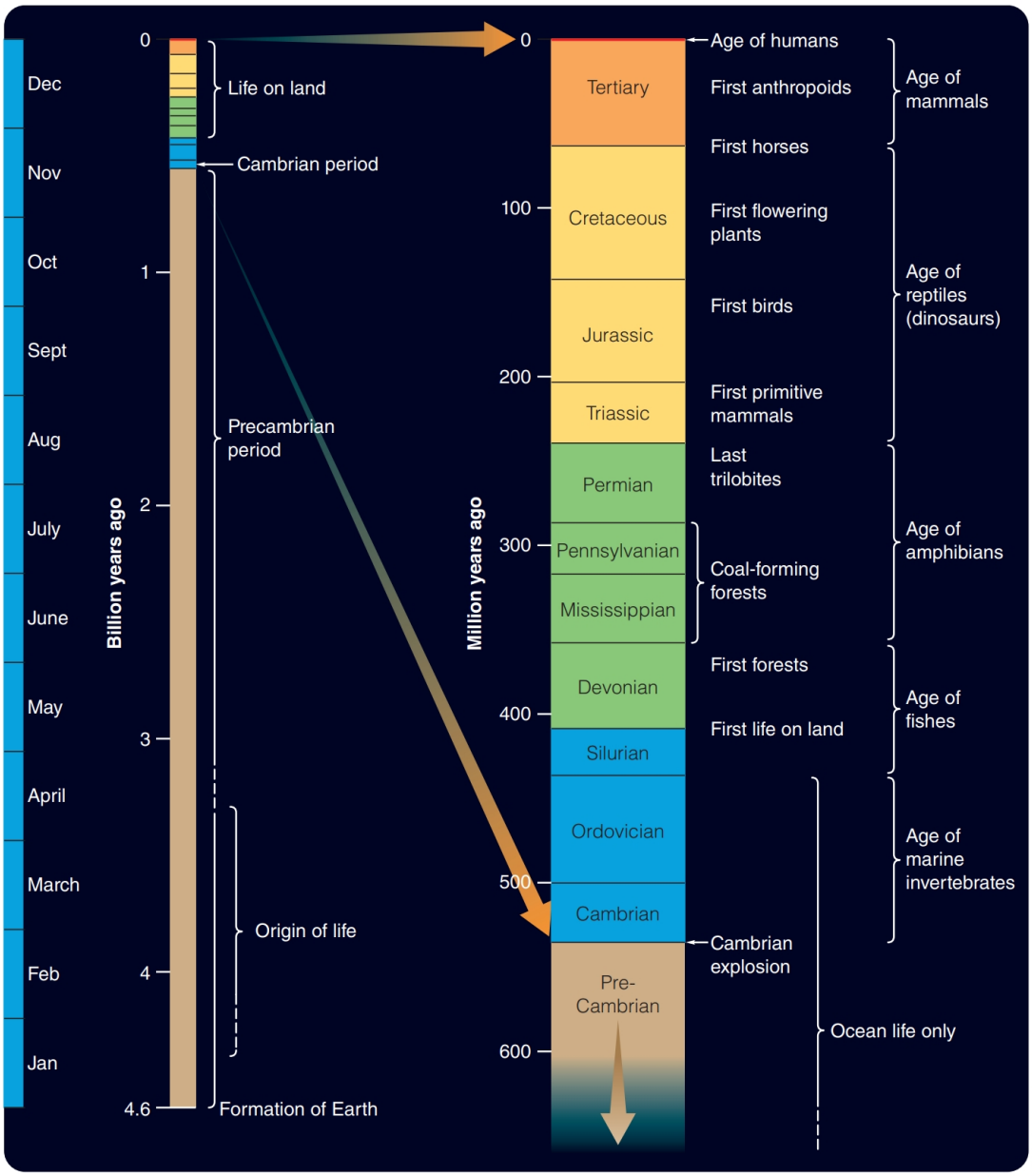


Figure 15.6 Complex life has developed on Earth only recently. If the entire history of Earth is represented as a timeline (left), you have to examine the end of the line closely to see details such as life leaving the oceans and dinosaurs appearing. If we imagine this line as a year-long video, with Earth forming on January 1, humans would not appear until the last minutes of December 31.

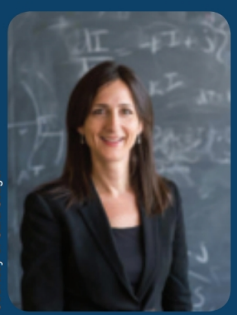
of years for evolution to solve the problems of how to move around the environment, obtain and use energy, reproduce, and survive disasters. Only very recently has life on Earth solved the problem of *intelligence*. Even so, very few species possess it and only one—our own—possesses the kind of intelligence required to communicate over interstellar distances. What does this tell us about the prospect of finding intelligent life elsewhere in the universe? We can break this question into two parts: how likely is it that a planet will develop life of any kind, and how likely is it that we could identify and communicate with that life if it were intelligent?

Life in Our Solar System

Of the hundreds of planets and moons in our solar system, which ones are most likely to host life? Scientists are in agreement that any world harbouring living things must

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CANADA'S ROLE IN THE GLOBAL STORY OF ASTRONOMY



Courtesy of Sara Seager

Sara Seager

Sara Seager

Canadian astronomer Sara Seager graduated from the University of Toronto in 1994, only a year before astronomy was forever changed by the discovery of a planet orbiting the star 51 Pegasi. This was the first exoplanet ever found orbiting a main-sequence star. It ignited the imaginations of thousands of astronomers and launched many careers. Five years later, Seager graduated from Harvard with a Ph.D. in astronomy specializing in the atmospheres of exoplanets. Since then, she has become one of the world's leaders in the study of exoplanets and their potential to support life. In 2007, Seager became a Professor of Physics and Planetary Science at the Massachusetts Institute of Technology (MIT).

Seager's research focuses on the atmospheres of exoplanets. Current technology doesn't allow astronomers to see surface details on exoplanets, which makes it very difficult to determine whether or not they host life. Seager's work on exoplanet atmospheres led her to wonder whether those atmospheres might reveal signs of life. Life on Earth has radically altered the chemistry of our atmosphere, adding gases such as oxygen and methane that can be detected over interstellar distances. Seager has developed techniques for detecting such "biosignature gases" in the atmospheres of exoplanets. She is also involved in the development of space telescopes designed to give us clearer views of both the surfaces and atmospheres of exoplanets.

In recognition of her pioneering work, Seager was awarded a prestigious 2013 MacArthur Fellowship.

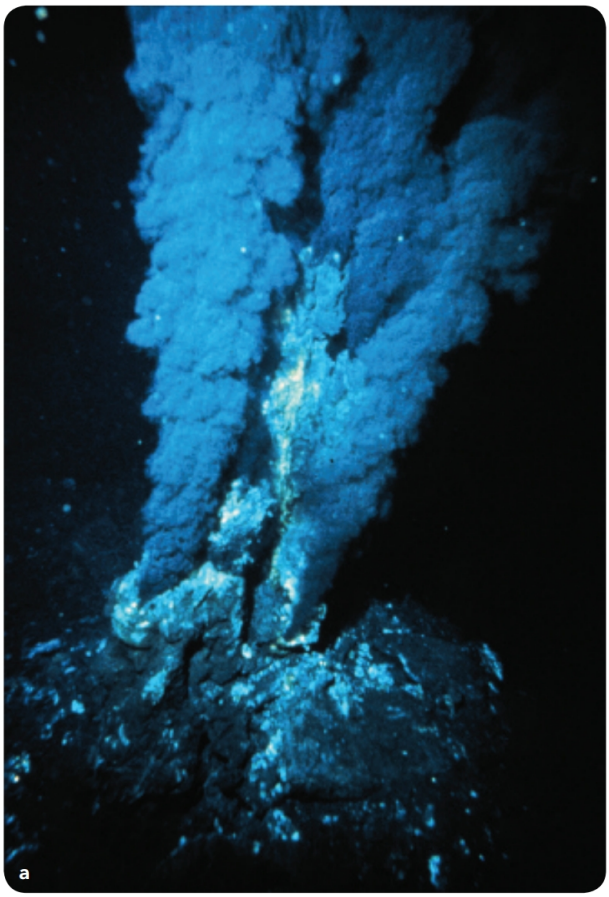
have significant quantities of some type of liquid. The liquid is necessary to provide a solvent in which organic chemicals can dissolve and react with one another. On Earth, the liquid that all life depends on is water. So, as astronomers and biologists look for life elsewhere in the solar system, the guiding principle they often use is "follow the water."

Water is a cosmically abundant substance. The most common molecule in interstellar space is molecular hydrogen, and the next most common is water. Water isn't the only chemical that can exist in a liquid state under the conditions typical of the surfaces of moons and planets. For example, Saturn's moon Titan, discussed in Chapter 14, has lakes of liquid methane and ethane. However, water has several chemical properties that set it apart from other common solvents and may make it a more suitable basis for life. Water is often described as the "universal solvent" because it is able to dissolve an unusually wide variety of substances, fostering chemical combinations that would not occur in any other solvent. Water also remains liquid over a wider range of physical conditions than many other solvents, providing stable environments for living organisms as well as resistance to fluctuations in body temperature. It's possible that there are forms of life in the universe very different from our own, some of which may not depend on water. However, in the absence of evidence of such kinds of life, it makes sense to concentrate the search for life on the one type of life we know can exist: life-like-us.

Many worlds in the solar system can be ruled out as hosts for life-like-us because liquid water cannot endure for long under the conditions that prevail there. The Moon and Mercury are airless, and water on the surface of either world would boil away into space immediately. Venus has traces of water vapour in its atmosphere, but it is too hot for liquid water to exist on the surface. The Jovian planets have deep atmospheres, and at a certain level water condenses into liquid droplets. However, it's difficult to imagine life-like-us persisting for long in the incredibly turbulent atmospheres of Jovian planets.

As you learned in Chapter 14, several of the moons of Jupiter almost certainly have large reservoirs of liquid water and could therefore host life. Jupiter's moon Europa appears to have a liquid-water ocean below its icy crust (Figure 14.3), and minerals dissolved in the water could provide a source of raw material for chemical evolution. Europa's ocean is kept warm and liquid now by tidal heating. There also may be liquid water layers under the surfaces of Ganymede and Callisto. The idea of searching for potential life on Europa was prompted by the discovery in 1997 of volcanic vents, called *black smokers*, on the bottom of the Pacific Ocean near the Galapagos Islands (see Figure 15.7). Mineral-rich water emerges from these hydrothermal vents more than 3 km under the surface of the ocean. Hundreds of species power their metabolism using the chemical energy from these

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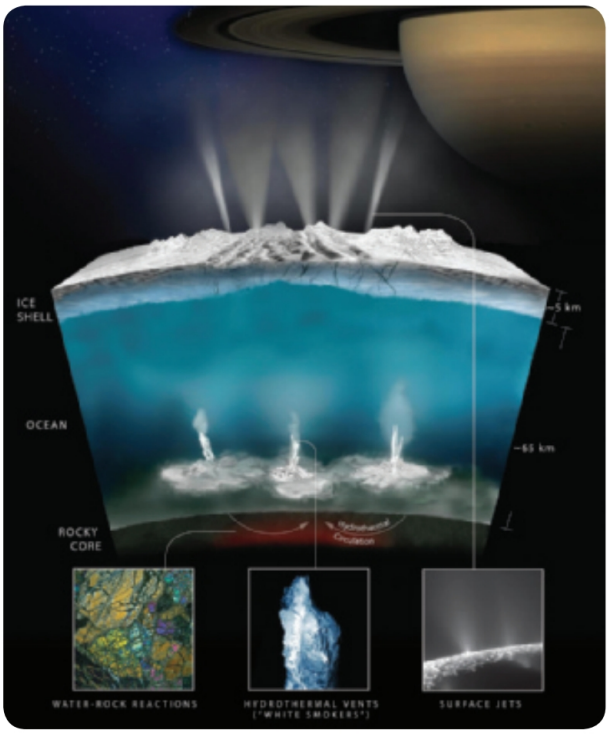


(a) and (b): NOAA Photo Library

Figure 15.7 (a) A view of a "black smoker" hydrothermal vent captured by the deep-sea submarine. (b) Hot, black water is a source of chemicals that sustain the tubeworms and other organisms that thrive in this habitat without sunlight.

vents instead of sunlight. If similar conditions exist in the oceans of Europa, perhaps life may exist there too, despite the absence of sunlight.

Jupiter isn't the only planet whose moons may host life. Observations of Saturn's moon Enceladus made by the Cassini spacecraft demonstrated that salty water is vented from cracks in the ice at its south pole. The water



NASA/JPL-Caltech/Southwest Research Institute

Figure 15.8 Observations of water venting from Enceladus's south pole hint at the existence of hydrothermal vents. Hydrothermal vents may provide an energy source for life in the waters below the crusts of many Jovian moons, where sunlight cannot reach.

contains hydrogen gas, suggesting that it is in contact with an energy source at the bottom of Enceladus' subsurface ocean. This energy source may take the form of hydrothermal vents, similar to those on Earth (see Figure 15.8). Similar environments may exist on many moons within and beyond our solar system, making Jovian moons attractive targets in the search for extraterrestrial life.

Saturn's largest moon, Titan, is rich in organic molecules. Recall from Chapter 14 that sunlight converts the methane in Titan's atmosphere into organic smog particles that settle to the surface. We don't know of any chemical processes that could generate or sustain life under these conditions, but the environment shares enough similarities with the young Earth that it is fascinating to speculate about the possibilities. The extremely low surface temperature on Titan of −180°C suggests that chemical reactions there might occur so slowly as to make life unlikely, but we cannot be sure.

There is no conclusive evidence that any of the planets of our solar system host long-lived bodies of liquid water. However, as you learned in Chapter 13, there is a great deal of evidence that liquid water once flowed on the surface of Mars. Could life have developed on Mars billions of years ago and survived to the present day? So far, searches

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for signs of life on Mars are not encouraging. The robotic spacecraft *Viking 1* and *Viking 2* landed on Mars in 1976 and tested soil samples for living organisms (Figure 15.9). The results were ambiguous: some of the tests appeared to show that carbon was being processed by living organisms on Mars, while others showed no evidence for life. The scientific consensus is that the positive results were caused by non-biological chemical reactions, and that there remains no conclusive evidence for life on Mars.

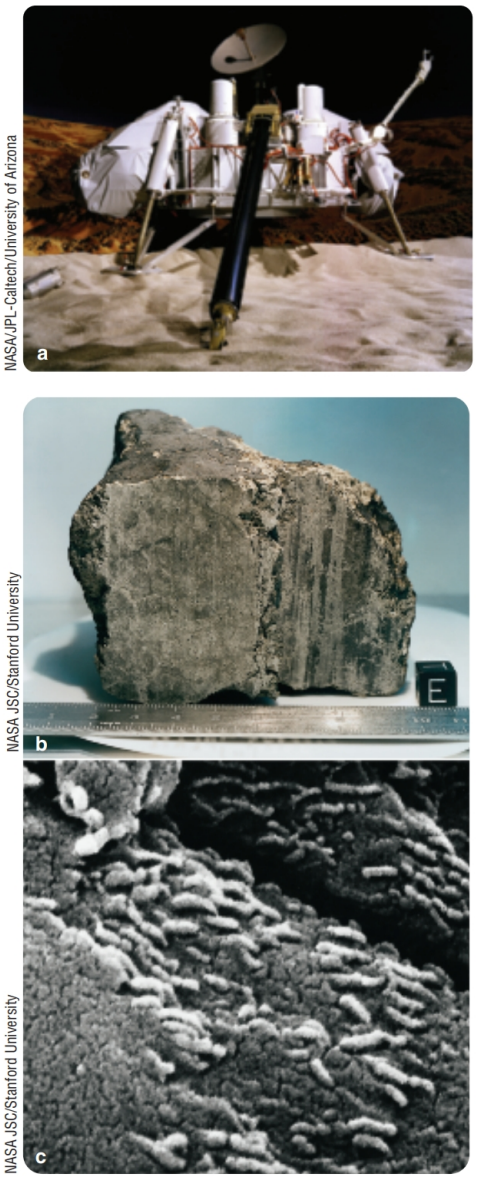


Figure 15.9 (a) A *Viking* lander model sits in a simulated Martian environment on Earth. A claw for grabbing rock and soil samples is at the end of the black arm. (b) Meteorite ALH 84001 is one of a dozen meteorites known to have originated on Mars. Its name means this meteorite was the first one found in 1984 near Antarctica's Allan Hills. (c) A research group studying ALH 84001 claimed that the meteorite contains chemical and physical traces of ancient life on Mars, including what appear to be fossils of microscopic organisms. This evidence has not been confirmed, and the claim continues to be tested and debated.

In 1996, headlines around the world announced the discovery of fossilized microorganisms in a Martian meteorite found in Antarctica (Figure 15.9). In addition to the supposed fossils, chemical signatures in the rock appeared to indicate the presence of formerly living material. Although the discovery was greeted optimistically, scientists soon showed that the features thought to suggest life could also have been produced through non-biological processes. One of the main skeptical claims was that the supposed fossils were so small that, had they been alive, there would have been no room inside their cell membranes for organelles. A minority of scientists still hold that these fossils may represent a distinct form of life not found on Earth. Conclusive evidence of life on Mars may have to wait until a geologist from Earth can scramble down dry Martian stream beds and crack open rocks looking for fossils.

We have learned that there is no strong evidence for the existence of life elsewhere in our solar system. So our search will have to take us to distant planetary systems.

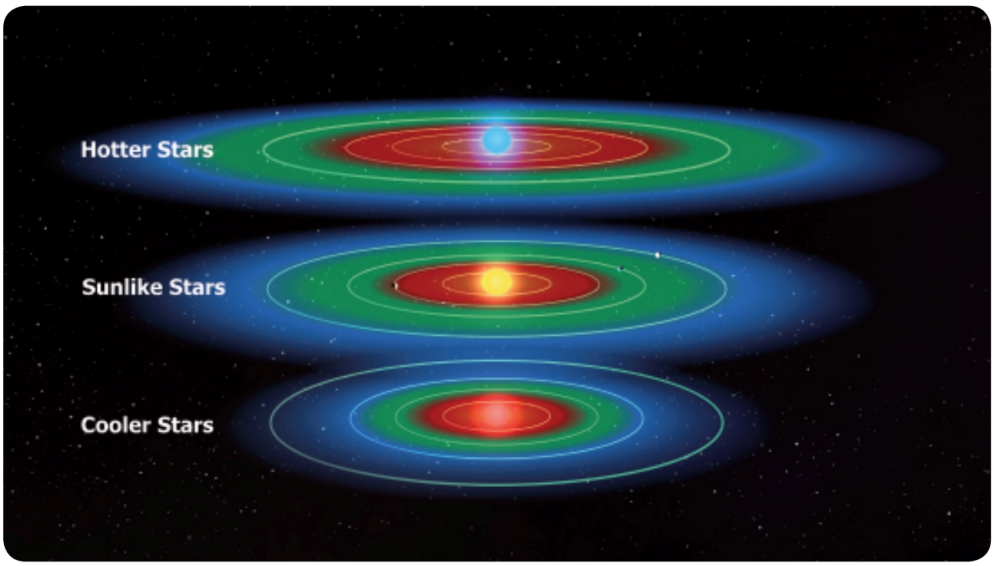
Life in Other Planetary Systems

Could life exist in other planetary systems? We can use what we have already learned about stars and planets to work out where habitable environments might be found.

For a planet to be a suitable home for living things, it must be in a stable orbit around its sun. Stable orbits are easily achieved in solar systems with only one star, such as our own. However, in binary or other multiple star systems whose stars are separated by distances of a few AU or less, stable orbits are much less common. In those cases, planets may be swallowed up by one of the stars or ejected from the system. Around half of the star systems in the Milky Way are single stars, and these are the ones believed most likely to support life on their planets.

You learned in Chapter 6 that the lifespan of a main-sequence star is related to its mass, with more massive stars having shorter lifespans. Remember that life on Earth required hundreds of millions of years to emerge and billions of years to produce intelligence. Very massive O and B stars have lifespans of only tens or hundreds of millions of years, which means they probably cannot support planets bearing complex life. If the history of life on Earth is at all representative, then stars more massive than about spectral type F5 are too short-lived for complex life to develop. Main-sequence stars of types G and K, and possibly some of the M stars, are the best candidates.

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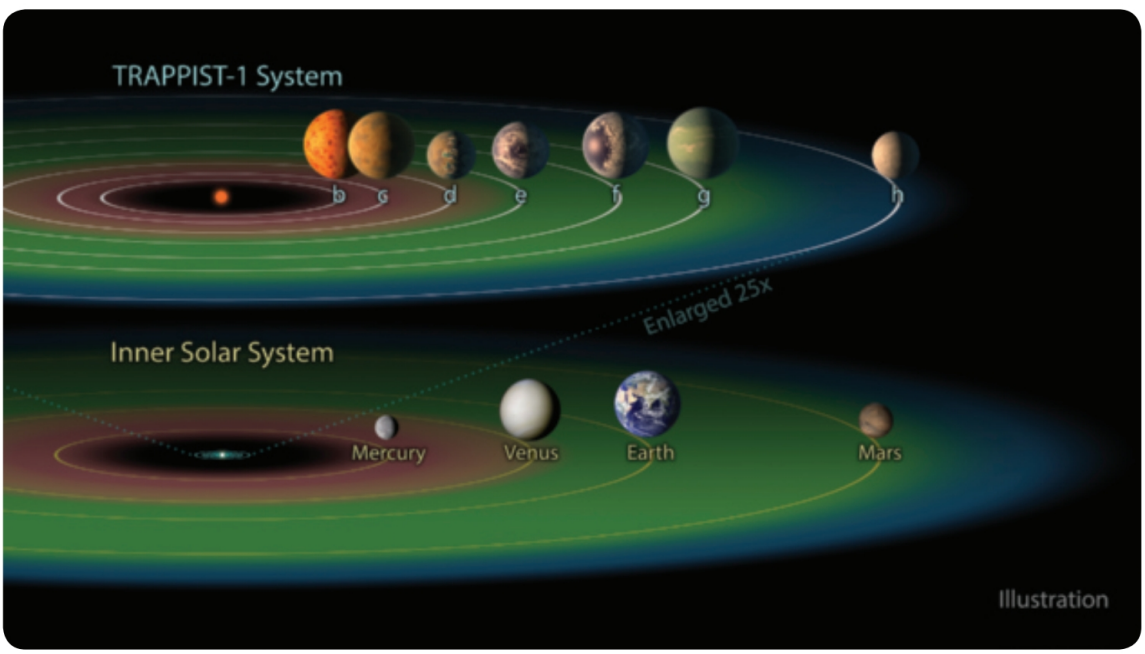


NASA/Kepler Mission/Dana Berry

Figure 15.10 Stellar habitable zone—the zone within a stellar system where water can exist in a liquid state. In this diagram, habitable zones of various stars are shown (coloured green): The hotter the star, the wider and farther away the habitable zone is. In our solar system, Venus and Earth are within habitable zone, and Mars is on the outer edge.

For planets in stable orbits around long-lived stars, the next most important factor to consider is their temperature. Astronomers have defined a **habitable zone** around a star as a region within which planets have temperatures that permit water to remain liquid on their surfaces for long periods of time (Figure 15.10). The Sun's habitable zone extends from near the orbit of Venus to the orbit of Mars, with Earth in the middle. A low-luminosity star, such as an M or K star, would have a narrow habitable zone close to the star, while a high-luminosity star, such as a G or F star, would have a wider habitable zone farther from the star. There are currently dozens of known planets orbiting in the habitable zones of their stars. Some planetary systems, such as TRAPPIST-1 (Figure 15.11), even contain multiple potentially habitable planets.

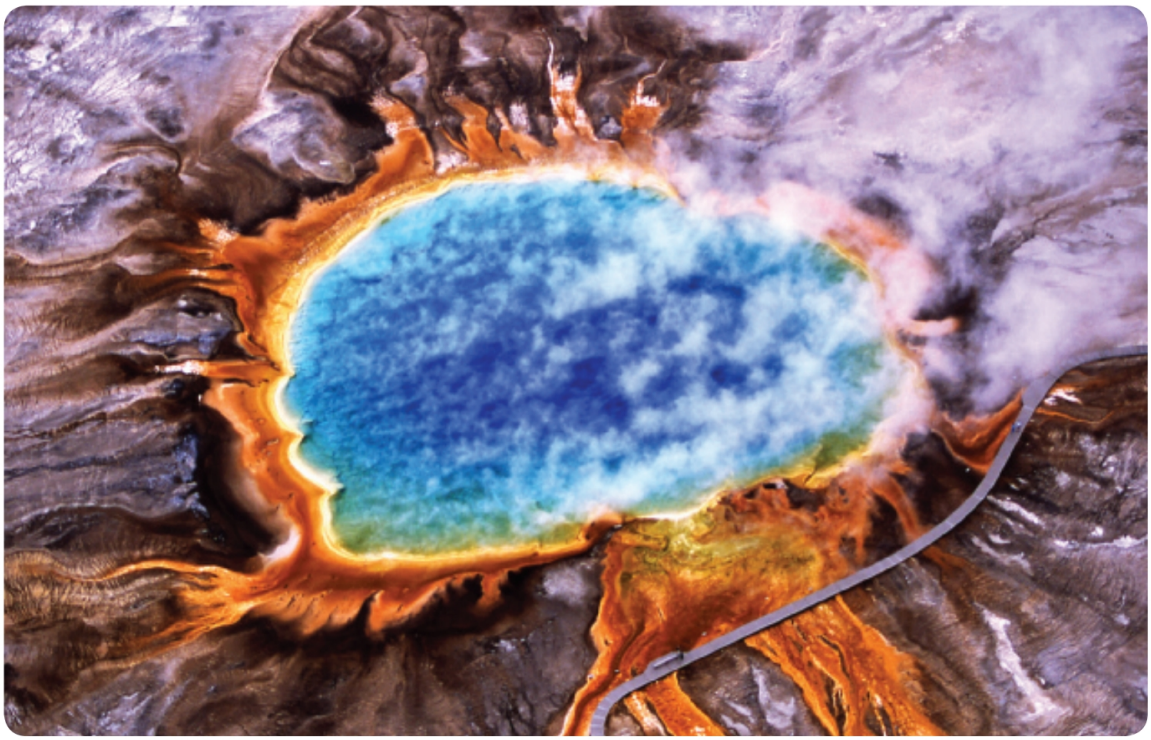
habitable zone A region around a star within which planets have temperatures that permit the sustained existence of liquid water on their surfaces.



NASA/JPL-Caltech

Figure 15.11 The TRAPPIST-1 system contains seven known planets, including three that are within its habitable zone. The parent star is an M star, so the habitable zone (shown in green) is narrow and close to the star. Planets e, f, and g lie within it. Their proximity to the star may mean that they are all tidally locked, with one face pointing perpetually to the star, the same way that one side of the Moon always points to Earth.

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Jim Peako/National Park Service

Figure 15.12 Organisms can live in environments that humans consider impossibly hostile. Colonies of thermophilic (heat-loving), single-celled organisms thrive around the edge of Yellowstone National Park's Grand Prismatic Spring at temperatures up to 72°C, producing the green pigments. The blue water in the centre of the pool is too hot even for thermophiles.

Scientists are finding life on Earth in places previously judged inhospitable, such as the bottoms of ice-covered lakes in Antarctica and far underground inside solid rock. Life has also been found in boiling hot springs with highly acidic water (Figure 15.12), and on cooling rods of nuclear reactors. As a result, it is difficult for scientists to pin down a range of environments and state with certainty that life cannot exist outside those conditions. In addition, the Jovian moons of our solar system that contain subsurface oceans lie far outside the Sun's conventional habitable zone. So, although we are used to imagining that life will be found on temperate planets inside the habitable zones of long-lived stars, the tenacity and resilience of Earth's life forms make it seem possible that life may exist in other locations.

15.3 Intelligent Life in the Universe

Visiting extrasolar planets is currently beyond our technological means. If we can't go visit, can we still hope to communicate with extraterrestrial civilizations?

Travel Between the Stars

The distances between stars are almost incomprehensible. The *New Horizons* spacecraft is one of the fastest devices ever built by humans, but even it would take 90 000 years to reach the nearest star. Even with spaceships that could approach the speed of light, it would take years to reach the closest stars and decades to reach stars like TRAPPIST-1. The energy cost would be staggering. The technology to transport humans at such speeds is well beyond us at present.

Could there be aliens who have overcome these challenges and visited Earth? Scientists have studied "unidentified flying objects" (UFOs) for decades and have never found any credible evidence that Earth is being visited or has ever been visited by aliens (see **How Do We Know? 15.1**). Instead, searches for extraterrestrial intelligence focus on attempts to send or receive communications, typically using light.

Radio Communication

Even before humans began to use radio to communicate across the Earth, some had speculated whether radio waves might be used to communicate across interstellar

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HOW DO WE KNOW? 15.1

UFOs and Space Aliens

If you conclude that there is likely to be life on other worlds, you might be tempted to use UFO sightings as evidence to test your hypothesis. Scientists don't do this for two reasons.

First, the evidence of UFO sightings is rarely reported in a credible way. When the evidence is delivered in the form of blurry pictures in tabloid newspapers or shaky videos on subscriber-hungry social media accounts, it does not inspire confidence that the data are reliable. Science relies on methods such as peer review to ensure the credibility of exceptional claims. If a scientist believed they had evidence for the existence of extraterrestrial intelligence, that evidence would normally be submitted to the scrutiny of their peers, not posted on social media or sold to the highest bidder.

Second, few UFO sightings survive careful examination. Most are deliberate hoaxes, and the rest seem to be unintentional misinterpretations of natural events or human-made objects. They don't meet the usual standards of scientific evidence, such as leaving convincing physical evidence or being independently verified by multiple unbiased observers. In an age when billions of people across the globe carry high-resolution cameras in their pockets, it's reasonable to ask why no two of them have ever provided clear photos of the same alien spacecraft. The simplest explanation consistent with the evidence is that Earth is simply not being visited by intelligent aliens.

In short, despite claims to the contrary there is no dependable evidence that Earth has been visited by aliens in recorded human history, or at any earlier time from which physical evidence survives. That's too bad. A confirmed visit by intelligent creatures from beyond our solar system would answer many questions and help us better understand our place in the cosmos.



© Dagfinn Rapp

This mysterious spiral appeared over the skies of Norway in 2009. Some claimed it was evidence of extraterrestrial activity—a wormhole, or warp drive. In the end, it was shown to be a malfunctioning Russian rocket spiralling out of control.

distances. Radio waves travel at the speed of light and require relatively little energy to produce. They can also pass relatively freely through the interstellar medium. Yet a conversation with aliens using radio waves would be a slow one: a conversation with aliens living on a planet in the TRAPPIST-1 system, 40 light-years away, would be punctuated by gaps of 80 years while radio signals made the roundtrip journey. Still, the method is one of the most promising we have.

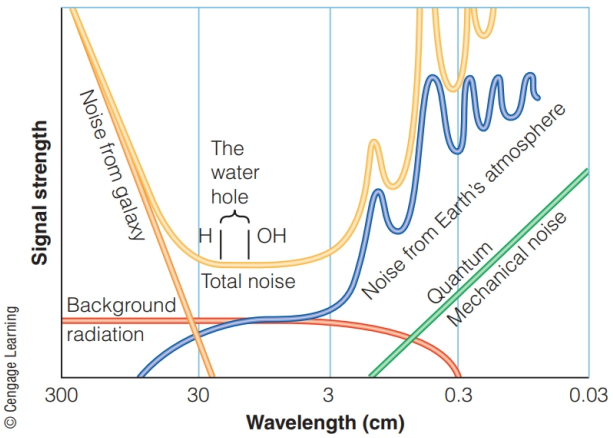
With the construction of the first radio telescopes in the 1950s, radio astronomers began to search the cosmos for messages from potential extraterrestrial civilizations encoded in the frequency or amplitude of radio waves. This field of study is known as **SETI**, the search for extraterrestrial intelligence. The first such project, Ozma (named after the queen of the Land of Oz from children's stories), was organized and conducted by SETI pioneer Frank Drake in 1960. In the decades since, dozens of different search strategies have been attempted.

How can we know what type of signal aliens might send? Some constraints come from basic physics: wavelengths longer than 100 cm would get lost in the background noise of the Milky Way Galaxy, while wavelengths shorter than about 1 cm are absorbed by Earth's atmosphere. Between those wavelengths is a radio window that is open for communication. Even this restricted window contains millions of possible radio-frequency bands and is too wide to monitor easily, but astronomers may have found a way to narrow the search. The 21-cm spectral line of neutral hydrogen and the 18-cm line of OH occur within this window (Figure 15.13). The interval between those lines has low background interference and is named the **water hole** because H plus OH yields

SETI The search for extraterrestrial intelligence.

water hole The interval of the radio spectrum between the 21-cm hydrogen emission line and the 18-cm OH emission line; wavelengths likely to be used in the search for extraterrestrial life.

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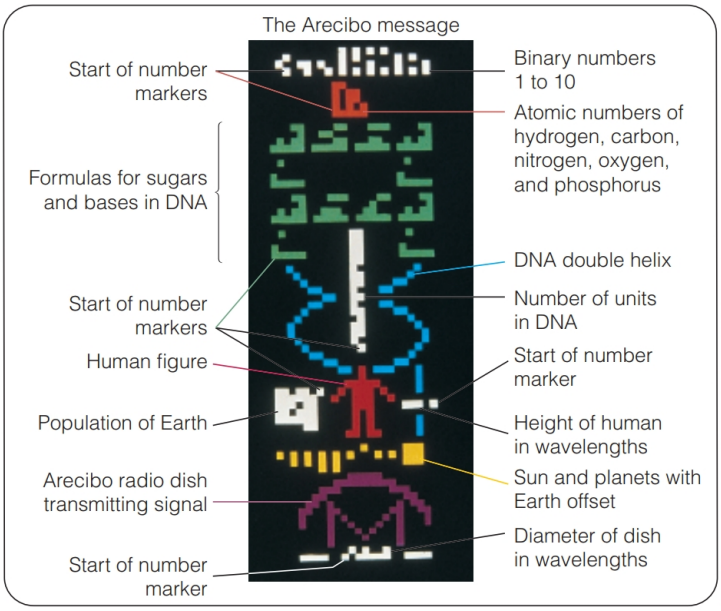
Figure 15.13 Radio noise from various astronomical sources makes it difficult to detect distant signals at wavelengths longer than 100 cm or shorter than 1 cm. In this range, radio emission lines from H atoms and from OH molecules mark a small wavelength range, named the water hole, that may be a likely channel for communication.

water. Any civilizations sophisticated enough to do radio astronomy would almost certainly examine the universe at these wavelengths simply because H and OH are two of the most abundant radio-emitting chemicals in the universe. Many radio searches have been conducted for signals arriving in the wavelength range of the water hole. So far, none have been detected. However, this has not deterred SETI researchers. SETI pioneer Dr. Jill Tarter likens the portion of the cosmos searched so far to a glass of water in all the oceans of Earth.

Rather than just wait passively for signals from extraterrestrial civilizations, some astronomers have broadcast signals of their own. In 1974, a group of astronomers led by Frank Drake and Carl Sagan decided to broadcast a simple message of greeting toward the globular cluster M13, 26 000 ly away, using the Arecibo radio telescope (Figure 15.14). When the signal arrives 26 000 years in the future, would its recipients be able to decode it?

The Arecibo message is intended to be decoded by beings about whom we know nothing except that they build radio telescopes. The message is encoded as a string of 1679 pulses and gaps, arranged in 73 rows of 23 pulses or gaps. When decoded, the message contains basic information about our planet and our species, including a crude diagram of a human body and the solar system, as well as information about our mathematical systems and our biology. The Arecibo message was not the only one of its kind. The 70 m Evpatoria Planetary Radar dish in Yevpatoria, Crimea has transmitted several similar messages. In 2008, it sent a high-powered digital radio signal called A Message from Earth (AMFE) toward Gliese 581 c—a large, terrestrial exoplanet orbiting the M star Gliese 581, approximately 20 ly from Earth. Astronomers chose to send the message to this planet because they believed it may be capable of supporting life. The message beamed by the telescope was a digital time capsule consisting of photos, drawings, and text messages selected by the public. The signal will reach the planet in 2029.

The search continues, but radio astronomers struggle to hear anything against the worsening babble of radio signals from human civilization. Some astronomers have begun to develop techniques for extraterrestrial communication—both sending and receiving—using visible-light lasers. Others are exploring even more exotic methods. Ultimately their success will depend on how many inhabited worlds there are in the cosmos, and whether any of them are close enough to Earth to allow for two-way communication. SETI pioneers Giuseppe Cocconi and Philip Morrison from Cornell University concluded their pioneering 1959 paper, titled "Searching for Interstellar Communications," with the following famous message: "The probability of success is difficult to estimate; but if we never search, the probability of success is zero."



Arecibo Observatory/Cornell University/NAIC/NSF/F. Drake, R. Isaacman, L. May, and J. Walker

Figure 15.14 The Arecibo message describes life on Earth (colour added for clarity). Binary numbers give the height of the human figure (1110) and the diameter of the telescope dish (100101111110) in units of the wavelength of the signal, which is 12.3 cm.

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How Many Inhabited Worlds?

Given enough time, SETI searches will find other worlds with civilizations, assuming that there are at least a few out there. If extraterrestrial intelligence is widespread, scientists should find signals relatively soon—within the next few decades. But if it is rare, it may take much longer.

Using simple arithmetic you can estimate the number of technological civilizations in the Milky Way Galaxy with which you might communicate. Call this number N_c—the number of communicating civilizations. The formula proposed to compute N_c is named the **Drake equation** after the radio astronomer Frank Drake, a pioneer in the search for extraterrestrial intelligence. The equation looks like this:

$$N_c = R_* \times f_p \times n_{HZ} \times f_L \times f_i \times f_c \times L$$

R_* is the rate at which stars form in our galaxy, in stars per year. f_p represents the fraction of stars that have planets. The factor n_{HZ} is the average number of planets in the habitable zone in each solar system. The factor f_L is the fraction of those planets on which life begins, and f_i is the fraction of those where life evolved to intelligence. f_c is the fraction of planets with intelligent life that attempt to communicate over interstellar distances. Finally, L is the length of time (in years) over which a communicating civilization actively communicates.

Most of the parameters in the Drake equation are difficult to estimate. We know that the rate of star formation in the Milky Way, R^*, is approximately 1.5 to 3 stars per year. Similarly, searches for exoplanets have revealed that the fraction of stars with planets, f_p, is nearly 100 percent. The number of planets in the habitable zone for stars that have planets, n_{HZ}, is not yet well constrained by our observations. Estimates from exoplanet searches suggest this number may be around 10 percent, but it could be higher or lower. As we have just learned, the focus on habitable planets may be too narrow: a more comprehensive calculation would take into account Jovian moons, which might someday be discovered to be the preferred home of life elsewhere in the universe.

Drake equation The equation that estimates the total number of communicative civilizations in the Milky Way Galaxy.

The remaining parameters in the Drake equation all have to do with the development and behaviour of extraterrestrial life. With only our own biological and cultural history as basis for speculation, it's impossible to draw general conclusions about life on other worlds. For example, although there are many worlds within our own solar system that have had long-lived liquid water, most of them don't seem to have developed life, suggesting that f_L might be a very low number. However, as we continue the exploration of our own and nearby solar systems, that view might change radically.

In Table 15.1 we have given some optimistic and pessimistic estimates for the parameters of the Drake equation to give a general idea of the possible outcomes. As you can see, the results differ dramatically: in the pessimistic view we are perhaps the only communicating civilization in the Milky Way, while in the optimistic view there may be tens of millions of communicating civilizations out there right now. One of those civilizations might be in our cosmic backyard, ready to talk.

The wide disparity in possible outcomes of the Drake equation testifies to how much remains to be learned about life on other worlds.

Table 15.1 | The Number of Technological Civilizations per Galaxy

		Estimates	
	Variables	**Pessimistic**	**Optimistic**
R_*	Rate of star formation in our galaxy (stars/year)	1.5	3
f_p	Fraction of stars with planets	0.7	1
n_{HZ}	Number of planets per star that lie in the habitable zone	0.01	1
f_L	Fraction of suitable planets on which life begins	0.001	1
f_i	Fraction of living planets where life evolves to intelligence	0.001	1
f_c	Fraction of planets with intelligence that actively communicate	0.01	1
L	Lifetime of a communicating civilization (years)	100	1×10^7
N_c	Number of communicative civilizations per galaxy	1.05×10^{-8}	3×10^7

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The **Big Picture**

What Are We?

You are made of very old atoms. The matter you are made of appeared in the big bang and was cooked into a wide range of elements inside stars. Your atoms may have been inside two or three generations of stars before they became part of a nebula that contracted to form the Sun and the planets of the solar system.

Your atoms have been part of Earth for the last 4.6 billion years. They have been recycled many times through dinosaurs, stromatolites, fish, bacteria, grass, birds, worms, and other living things. Now you are using these atoms, but when you are done with them, they will be used again and again.

When the Sun swells into a red giant star and dies in a few billion years, Earth's atmosphere and oceans will be driven away, and at least the outer few kilometres of Earth's crust will be vaporized and blown outward to become part of the nebula around the white-dwarf remains of the Sun. Your atoms are destined to return to the interstellar medium and will become part of future generations of stars, planets, and perhaps living beings.

The message of astronomy is that humans are not just observers. We are participants, we are part of the universe. We are how the universe knows itself. Among all the galaxies, stars, planets, planetesimals, and bits of matter, humans are objects that can think, and that means we can understand what we are.

Is the human race the only thinking species? If so, we bear the sole responsibility to understand and admire the universe. The detection of signals from another civilization would demonstrate that we are not alone, and such communication would end the self-centred isolation of humanity and stimulate a re-evaluation of the meaning of human existence. We may never realize our full potential as humans until we communicate with non-human intelligent life.

Review and **Discussion Questions**

Review Questions

1. If life is based on information, what is that information?
2. What would happen to a life form if the information handed down to offspring was always the same? How would that endanger the future of the life form?
3. How does the DNA molecule produce a copy of itself?
4. Give an example of natural selection acting on new DNA patterns to select the most advantageous characteristics.
5. What evidence do scientists have that life on Earth began in the sea?
6. Why do scientists think that liquid water is necessary for the origin of life?
7. What was the significance of the Miller-Urey experiment?
8. How does intelligence make a creature more likely to survive?
9. Why are upper-main-sequence (high-luminosity) stars unlikely sites for intelligent civilizations?
10. Why is it reasonable to suspect that travel between stars will remain very difficult even as our technology develops?
11. How does the stability of technological civilizations affect the probability that Earth can communicate with them?
12. What is the water hole, and why would it be a good "place" to look for other civilizations?
13. The star cluster NGC 2264 contains cool red giants and main-sequence stars from hot blue stars all the way down to red dwarfs. Discuss the likelihood that planets orbiting any of these stars might be home to life. Don't neglect to estimate the age of the cluster.
14. What forms have our attempts to communicate with extraterrestrial civilizations taken?
15. Why do SETI scientists search for radio signals from extraterrestrials in the "water hole" wavelength range?
16. **How Do We Know?** Why are scientists skeptical about claims that Earth is being visited by aliens?

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Discussion Questions

1. Do you expect that hypothetical alien recipients of the Arecibo message will be able to decode it? Why or why not?
2. How do you think the detection of extraterrestrial intelligence would be received by the public? Would it be likelier to upset, or confirm, humans' beliefs about themselves and the world?
3. What do you think it would mean if decades of careful searches for radio signals for extraterrestrial intelligence turn up nothing?
4. What kinds of observations would be needed to fill in the parameters of the Drake equation? How would you modify the equation to make it more immediately useful in the search for extraterrestrial life?

Learning to Look

1. The star cluster shown in the image below contains cool red giants and main-sequence stars from hot blue stars all the way down to red dwarfs. Discuss the likelihood that planets orbiting any of these stars might be home to life. (*Hint*: Estimate the age of the cluster.)



European Space Agency & NASA

2. If you could search for life in the galaxy shown in the image below, would you look among disk stars or halo stars? Discuss the factors that influence your decision.



ESO

STUDY TOOLS

IN THE BOOK

- Tear Out the Review Card on *Life on Other Worlds.*

ONLINE

- Visit MindTap® for ASTRO3 at nelson.com/student
- eBook
- Interactive Quizzing
- Animations
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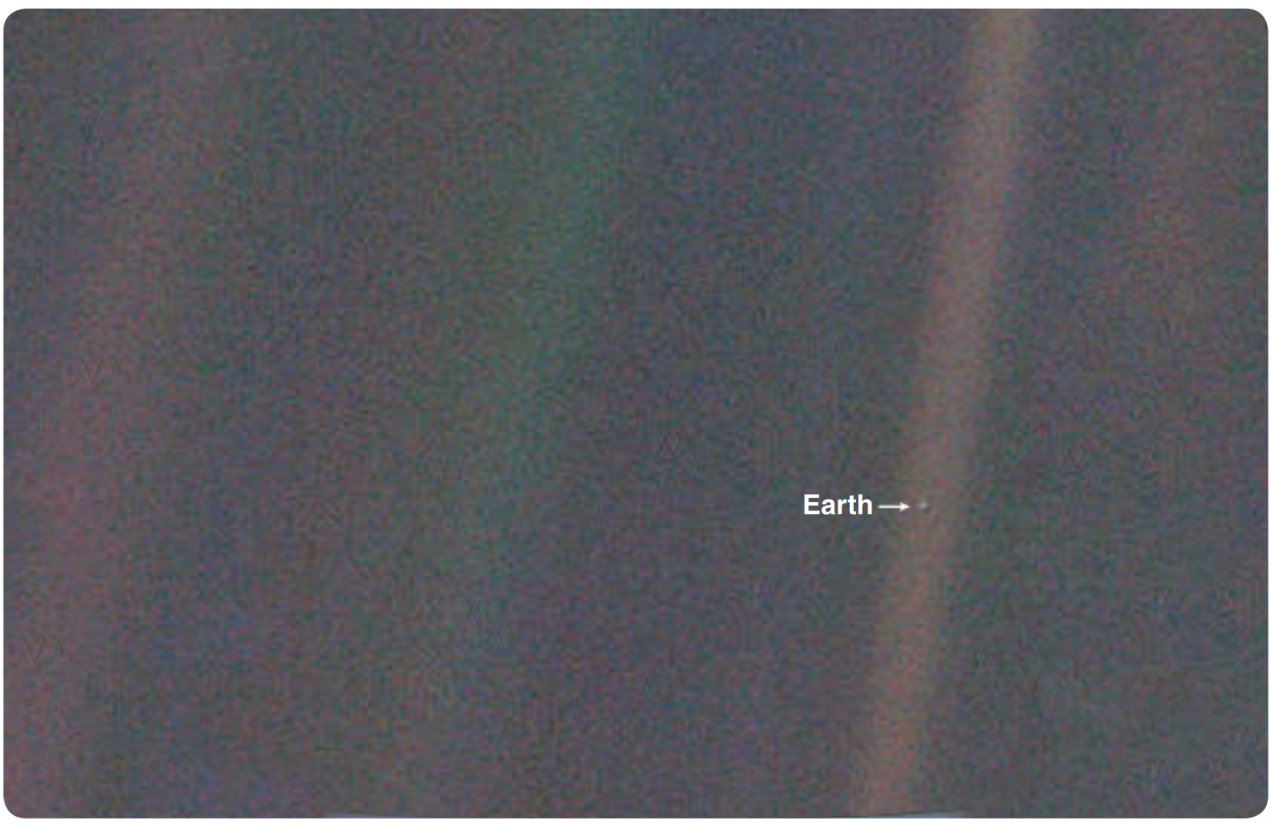
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AFTERWORD

> The aggregate of all our joys and sufferings, thousands of confident religions, ideologies and economic doctrines, every hunter and forager, every hero and coward, every creator and destroyer of civilizations, every king and peasant, every young couple in love, every hopeful child, every mother and father, every inventor and explorer, every teacher of morals, every corrupt politician, every superstar, every supreme leader, every saint and sinner in the history of our species, lived there on a mote of dust, suspended in a sunbeam.
>
> *Carl Sagan, American astrophysicist (1934–1996)*

Our journey together is over, but before we part company let's ponder one more time the primary theme of this book: humanity's place in the universe. Astronomy helps us comprehend the workings of stars, galaxies, and planets, but its greatest value lies in what it teaches us about ourselves. Now that you have surveyed astronomical knowledge, you can better understand your own position in nature.

The word *nature* conjures up images of rabbits in a forest glade or blue-green oceans or windswept mountaintops. As diverse as these images are, they are all earthbound. Having studied astronomy, you can see nature as a beautiful mechanism composed of matter and energy interacting according to simple rules to form galaxies, stars, planets, mountaintops, ocean depths, forest glades, and people.



Earth photographed by *Voyager 1* from the edge of the solar system. The vertical beams are sunlight reflected inside the camera.

NASA

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Perhaps the most important astronomical lesson is that humanity is a small but important part of the universe. Most of the universe is probably lifeless. The vast reaches between the galaxies appear to be empty of all but the thinnest gas, and stars are much too hot to preserve the chemical bonds that seem necessary for life to survive and develop. It seems that only on the surfaces of planets and moons that are "just right," where temperatures are moderate, can atoms link together in special ways to form living matter.

Because life is special, intelligence is very precious. The universe may contain many planets devoid of life, planets where the wind has blown unfelt for billions of years. There may also exist planets where life has developed but has not become complex, planets on which the wind stirs wide plains of grass and rustles through dark forests. It is intelligence, human or non-human, that gives meaning to the landscape.

Science is the process by which Earth intelligence has tried to understand the physical universe. However, science is not the invention of new devices or processes. It does not create home computers, cure the mumps, or manufacture plastic spoons; these are products of engineering and technology, the adaptation of scientific understanding for practical purposes. Science is also the understanding of nature, and astronomy is that understanding on the grandest scale. Astronomy is the science by which the universe, through human intelligence, tries to understand its own existence.

As the primary intelligent species on this planet, we are the custodians of a priceless gift: a planet filled with living things. This is especially true if life is rare in the universe. In fact, if Earth is the only inhabited planet, our responsibility is overwhelming. We are the only creatures who can take action to preserve the existence of life on Earth, and, ironically, our own actions are the most serious hazards.

The future of humanity is not secure. We are trapped on a tiny planet with limited resources and a population growing faster than our ability to produce food. In our efforts to survive, we have already driven many organisms to extinction and now threaten others. But even if we control our population and conserve and recycle our resources, life on Earth is doomed. In 5 billion years, the Sun will leave the main sequence and swell into a red giant, incinerating Earth.

To survive, humanity must eventually leave Earth and search for other planets. Travel to the stars will perhaps be the greatest challenge we have ever faced. We do have a few billion years to prepare for this next great adventure, and a billion years is a fairly long time. We can use that time to increase our knowledge of the universe and prepare to journey to the stars bravely but responsibly. Who can tell what future discoveries lie ahead in this most epic of quests! Perhaps we will finally answer that all-important question: are we alone?

But one thing is clear today. If we hope to survive and aim for the stars, we must do it together as one species, united in a common cause. This calls for drastic changes in our behaviour toward each other and other living things, and in our attitude toward our planet's resources. Our very survival requires us to become dependable custodians of our planet, preserving it, admiring it, and trying to understand it. Will we succeed? That depends on the choices we make. We are not perfect, but we have the gift of intelligence and that may be the most wonderful thing this planet has ever produced. The future of our planet, our very own spaceship in the cosmos, is in our hands. Let's guard it well.

> The human brain now holds the key to our future. We have to recall the image of the planet from outer space: a single entity in which air, water, and continents are interconnected. That is our home.
>
> *David Suzuki, Canadian scientist and environmental activist*

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APPENDIX

A

Units and Astronomical Data

The Metric System and SI Units

A system of measurement is based on the three fundamental units for length, mass, and time. By international agreement, there is a preferred set of metric units known as the *Système International d'Unités* (SI units) that is based on the metre, kilogram, and second.

Density should be expressed in SI units as kilograms per cubic metre, but no human hand can enclose a cubic metre, so that unit does not help you easily grasp the significance of a given density. Instead, this book refers to density in grams per cubic centimetre. A gram is roughly the mass of a paperclip, a cubic centimetre is the size of a small sugar cube, and a density of 1 g/cm^3 equals the density of water, all tangible units.

The International System of Units has been adopted as the official system of weights and measures by all nations in the world except for Myanmar (formerly Burma), Liberia, and the United States. This book expresses most quantities only in metric units. However, for conceptual purposes, occasionally some quantities are better expressed in more commonly used units. Instead of saying that the average person would weigh 133 N on the Moon, it might help some readers to see that weight described as 30 lb.

You might wonder how we standardize the basic units such as kilogram, metre, and second. In other words, how do we all agree exactly how long a metre is or how long a second is? These quantities are defined with respect to fundamental constants in nature that scientists have measured very accurately. For example, in 2019 the metre was officially defined at the General Conference on Weights and Measures to be the distance travelled by light in a vacuum in 1/299 792 458 of a second. But this definition depends on what a second is. In 2019, the second was also officially defined by carefully measuring a specific frequency of light emitted from a cesium atom to be 9192631770 Hz. The second is then defined using the inverse relationship between frequency and time. Finally, the kilogram was officially defined in 2019 in terms of a quantity known as the Planck constant, whose value has been measured to be $h = 6.62607015 \times 10^{-34}$ kg·m^2·s^{-1}. Since the metre and the second are already defined, this quantity can be used to work out what 1 kg is.

Temperature Scales

In astronomy, as in most other sciences, temperatures are expressed on the Kelvin scale, although the centigrade scale is also used. The centigrade scale is also called the Celsius scale after its inventor, the Swedish astronomer Anders Celsius (1701–1744). Temperatures on the centigrade scale are measured from the freezing point of water (0°C). Temperatures on the Kelvin scale are measured from absolute zero, the temperature of an object that contains no extractable heat (0 K, or −273 degrees centigrade). In practice, no object can be as cold as absolute zero, although laboratory apparatus have reached temperatures less than 10^{-6} K. The Kelvin scale is named after the Scottish mathematical physicist William Thomson, Lord Kelvin (1824–1907). A one degree centigrade change is equal to a 1 Kelvin change.

The Fahrenheit scale fixes the freezing point of water at 32°F and the boiling point at 212°F. Named after the German physicist Gabriel Daniel Fahrenheit (1686–1736), who made the first successful mercury thermometer in 1720, the Fahrenheit scale is used routinely only in the United States. To convert a temperature from the Fahrenheit to the Celsius scale, first subtract 32 and then multiply by a factor of 5/9. To convert a temperature from the Celsius to the Kelvin scale, add 273.

Astronomy Units and Constants

Astronomy, and science in general, is a way of learning about nature and understanding the universe. To test hypotheses about how nature works, scientists use observations of nature. The tables that follow contain some of

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the basic observations that support science's best understanding of the astronomical universe. Of course, these data are expressed in the form of numbers, not because science reduces all understanding to mere numbers, but because the struggle to understand nature is so demanding that science must use every good means available. Quantitative thinking—reasoning mathematically—is one of the most powerful techniques ever invented by the human brain. Numbers and mathematical analysis can be used to recognize patterns and build models of nature as well as verify our growing understanding of the universe.

Table A.1 defines units of measure commonly used by astronomers. Table A.2 gives physical constants such as the speed of light, plus basic astronomical data such as the mass and luminosity of the Sun. Table A.3 presents the characteristics of different spectral types of main-sequence stars. Tables A.4 and A.5, respectively, list the 15 nearest and the 15 brightest stars with their individual properties. The fact that these two star lists have almost no overlap is an important truth about stars that you can read more about in Chapter 6. Table A.6 gives the physical and orbital properties of the major planets in our solar system. Table A.7 lists the larger moons of each planet and their characteristics. The outer planets have many smaller moons that are not listed here.

Table A.1 | Units Used in Astronomy

1 angstrom (Å)	$= 10^{-8}$ cm
	$= 10^{-10}$ m
	= 10 nm
1 astronomical unit (AU)	$= 1.50 \times 10^{11}$ m
1 light-year (ly)	$= 6.32 \times 10^{4}$ AU
	$= 9.46 \times 10^{15}$ m
1 parsec (pc)	$= 2.06 \times 10^{5}$ AU
	$= 3.09 \times 10^{16}$ m
	= 3.26 ly
1 kiloparsec (kpc)	= 1000 pc
1 megaparsec (Mpc)	= 1 000 000 pc

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Table A.2 | Astronomical Constants

Velocity of light (c)	$= 3.00 \times 10^{8}$ m/s
Gravitational constant (G)	$= 6.67 \times 10^{-11}$ m^3/(s^2 kg)
Mass of H atom	$= 1.67 \times 10^{-27}$ kg
Mass of Earth ($M_\oplus$)	$= 5.98 \times 10^{24}$ kg
Earth equatorial radius ($R_\oplus$)	$= 6.38 \times 10^{6}$ m
Mass of Sun ($M_\odot$)	$= 1.99 \times 10^{30}$ kg
Radius of Sun ($R_\odot$)	$= 6.96 \times 10^{8}$ m
Solar luminosity ($L_\odot$)	$= 3.85 \times 10^{26}$ J/s
Mass of Moon	$= 7.35 \times 10^{22}$ kg
Radius of Moon	$= 1.74 \times 10^{3}$ km

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Table A.3 | Properties of Main-Sequence Stars

Spectral Type	Absolute Visual Magnitude (M_v)	Luminosity*	Temp. (K)	λ_{max} (nm)	Mass*	Radius*	Average Density (g/cm^3)
O5	−5.8	500 000	40 000	72.4	40.0	18.0	0.01
B0	−4.1	20 000	28 000	100	18.0	7.4	0.1
B5	−1.1	800	15 000	190	6.4	3.8	0.2
A0	+0.7	80	9900	290	3.2	2.5	0.3
A5	+2.0	20	8500	340	2.1	1.7	0.6
F0	+2.6	6.3	7400	390	1.7	1.4	1.0
F5	+3.4	2.5	6600	440	1.3	1.2	1.1
G0	+4.4	1.3	6000	480	1.1	1.0	1.4
G5	+5.1	0.8	5500	520	0.9	0.9	1.6
K0	+5.9	0.4	4900	590	0.8	0.8	1.8
K5	+7.3	0.2	4100	700	0.7	0.7	2.4
M0	+9.0	0.1	3500	830	0.5	0.6	2.5
M5	+11.8	0.01	2800	1000	0.2	0.3	10.0
M8	+16.0	0.001	2400	1200	0.1	0.1	63.0

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*Luminosity, mass, and radius are given as multiples of the Sun's luminosity, mass, and radius.

Table A.4 | The 15 Nearest Stars

Name	Distance (ly)	Distance (pc)	Apparent Visual Magnitude (m_v)	Absolute Magnitude (M_v)	Spectral Type
Sun			−26.7	4.8	G2
Proxima Cen	4.2	1.3	11.0	15.5	M6
α Cen A	4.4	1.3	0.0	4.4	G2
α Cen B	4.4	1.3	1.3	5.7	K5
Barnard's Star	5.9	1.8	9.5	13.2	M4
Wolf 359	7.7	2.4	13.5	16.7	M6
Lalande 21185	8.3	2.5	7.5	10.5	M2
α CMa A (Sirius A)	8.6	2.6	−1.5	1.4	A1
α CMa B (Sirius B)	8.6	2.6	8.4	11.3	white dwarf
Luyten 726-8A	8.7	2.7	12.6	15.4	M6
Luyten 726-8B	8.7	2.7	12.0	14.9	M5
Ross 154	9.7	3.0	11.0	13.6	M3
Ross 248	10.4	3.2	12.2	14.8	M6
ε Eri	10.5	3.2	3.7	6.2	K2
Luyten 789-6	10.9	3.3	12.2	14.6	M6

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Table A.5 | The 15 Brightest Stars

Star	Name	Apparent Visual Magnitude (m_v)	Distance (ly)	Absolute Magnitude (M_v)	Spectral Type
α CMa	Sirius	−1.47	8.6	1.4	A1
α Car	Canopus	−0.72	313	−5.6	F0
α Cen	Rigil Kentaurus	−0.29	4.3	4.1	G2
α Boo	Arcturus	−0.04	36	−0.3	K2
α Lyr	Vega	0.03	25	0.6	A0
α Aur	Capella	0.08	42	−0.5	G8
β Ori	Rigel	0.12	783	−6.8	B8
α CMi	Procyon	0.34	11	2.6	F5
α Eri	Achernar	0.50	144	5.1	B3
α Ori	Betelgeuse	0.58	424	−5.0	M2
β Cen	Hadar	0.60	522	−5.4	B1
α Aql	Altair	0.77	17	2.2	A7
α Cru	Acrux	0.81	320	−4.2	B0
α Tau	Aldebaran	0.85	65	−0.7	K5
α Vir	Spica	1.04	261	−3.5	B1

Note: © Cengage Learning. Data from the SIMBAD database, operated at CDS, Strasbourg, France.
For multiple star systems, the magnitude given is the combined light of all components; the spectral type is for the primary component.

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Table A.6 | Properties of the Planets

PHYSICAL PROPERTIES (EARTH = ⊕)

Planet	Equatorial Radius (km)	Equatorial Radius (⊕ = 1)	Mass (⊕ = 1)	Average Density (g/cm^3)	Surface Gravity (⊕ = 1)	Escape Velocity (km/s)	Sidereal Period of Rotation	Inclination of Equator to Orbit
Mercury	2440	0.38	0.055	5.43	0.38	4.3	58.65^d	0°
Venus	6052	0.95	0.815	5.20	0.90	10.4	243.02^d	177.3°
Earth	6378	1.00	1.00	5.52	1.00	11.2	23.93^h	23.4°
Mars	3396	0.53	0.107	3.93	0.38	5.0	24.62^h	25.2°
Jupiter	71 492	11.21	317.8	1.33	2.53	59.5	9.92^h	3.1°
Saturn	60 268	9.45	95.2	0.69	1.06	35.5	10.57^h	26.7°
Uranus	25 559	4.01	14.5	1.27	0.89	21.3	17.24^h	97.8°
Neptune	24 764	3.88	17.1	1.64	1.14	23.5	16.11^h	28.3°

h = hours; d = days

ORBITAL PROPERTIES

Planet	Semimajor Axis (AU)	Semimajor Axis (10^6 km)	Orbital Period (years)	Orbital Period (days)	Average Orbital Velocity (km/s)	Orbital Eccentricity	Inclination to Ecliptic
Mercury	0.39	57.9	0.24	87.97	47.9	0.206	7.0°
Venus	0.72	108.2	0.62	224.68	35.0	0.007	3.4°
Earth	1.00	149.6	1.00	365.26	29.8	0.017	0° (by definition)
Mars	1.52	227.9	1.88	686.95	24.1	0.093	1.9°
Jupiter	5.20	778.5	11.9	4332.6	13.1	0.049	1.3°
Saturn	9.58	1433.4	29.5	10 760	9.7	0.056	2.5°
Uranus	19.23	2876.7	84.0	30 687	6.8	0.047	0.8°
Neptune	30.10	4503.4	164.8	60 190	5.4	0.009	1.8°

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Table A.7 | Principal Satellites of the Solar System

Planet	Satellite	Radius (km)	Average Distance from Planet (10^3 km)	Orbital Period (days)	Orbital Eccentricity	Orbital Inclination
Earth	Moon	1738	384.4	27.32	0.055	5.1°
Mars	Phobos	14 × 12 × 10	9.4	0.32	0.018	1.0°
	Deimos	8 × 6 × 5	23.5	1.26	0.002	2.8°
Jupiter	Amalthea	135 × 100 × 78	182	0.50	0.003	0.4°
	Io	1820	422	1.77	0.000	0.3°
	Europa	1565	671	3.55	0.000	0.5°
	Ganymede	2640	1071	7.16	0.002	0.2°
	Callisto	2420	1884	16.69	0.008	0.2°
	Himalia	~85	11 470	250.6	0.158	27.6°
Saturn	Janus	110 × 80 × 100	151.5	0.70	0.007	0.1°
	Mimas	196	185.5	0.94	0.020	1.5°
	Enceladus	250	238.0	1.37	0.004	0.0°
	Tethys	530	294.7	1.89	0.000	1.1°
	Dione	560	377	2.74	0.002	0.0°
	Rhea	765	527	4.52	0.001	0.4°
	Titan	2575	1222	15.94	0.029	0.3°
	Hyperion	205 × 130 × 110	1484	21.28	0.104	~0.5°
	Iapetus	720	3562	79.33	0.028	14.7°
	Phoebe	110	12 930	550.4	0.163	150°
Uranus	Miranda	242	129.9	1.41	0.017	3.4°
	Ariel	580	190.9	2.52	0.003	0°
	Umbriel	595	266.0	4.14	0.003	0°
	Titania	805	436.3	8.71	0.002	0°
	Oberon	775	583.4	13.46	0.001	0°
Neptune	Proteus	205	117.6	1.12	~0	~0°
	Triton	1352	354.59	5.88	0.00	160°
	Nereid	170	5588.6	360.12	0.76	27.7°

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~ signifies "approximately"

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APPENDIX

B

Observing the Sky

Observing the sky with the naked eye is as important to modern astronomy as picking up pebbles is to modern geology. Neglecting the beauty of the sky is equivalent to geologists neglecting the beauty of the minerals they study. It would be quite appropriate for you to regard the night sky as the first natural wonder of the world. This supplement to Chapter 2 will help you get started observing the night sky for yourself.

The brighter stars in the sky are visible even from the centres of cities that have air and light pollution. But in the countryside, only a few kilometres beyond the cities, the night sky is a velvety blackness strewn with thousands of glittering stars. From a wilderness location, far from the city's glare, and especially from high mountains, the night sky is spectacular.

Using Star Charts

The constellations are a fascinating part of our cultural heritage. However, they can be difficult to learn because of Earth's motion. The constellations that appear above the horizon change with the time of night and the seasons.

Because Earth rotates eastward, the sky appears to rotate westward around Earth, a fact you have known since childhood. A constellation that is visible shortly after sunset will appear to move westward, and in a few hours it will disappear below the western horizon. Other constellations will rise in the east, and so the sky changes gradually through the night.

In addition, Earth's orbital motion makes the Sun appear to move eastward among the stars. Each day the Sun moves about twice its own diameter, about one degree, eastward along the ecliptic. Consequently, each night at sunset, the constellations are about 1 degree farther toward the west.

For instance, Orion is visible in the evening sky in January, but as the days pass, the Sun moves closer to Orion. By March, Orion is difficult to see in the western sky soon after sunset. By June, the Sun is so close to Orion that the constellation sets with the Sun and is not visible. Not until late July is the Sun far enough past Orion for the constellation to become visible rising in the eastern sky just before dawn.

Because of the rotation and orbital motion of Earth, you need more than one star chart to map the sky. Which chart you select depends on the month and the time of night. The charts printed on the next two pages show the evening sky for each season, as viewed from the northern hemisphere at a latitude typical of southern Canada or central Europe.

To use the charts, select the appropriate chart and hold it overhead, as shown in Figure B.1. If you face south, turn the chart until the words southern horizon are at the bottom of the chart. If you face other directions, turn the chart appropriately. Note that hours are in Standard Time; for Daylight Savings Time (spring, summer, and the first half of fall in Canada) add 1 hour.



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Figure B.1 To use the star charts in this book, select the appropriate chart for the season and time. Hold it overhead and turn it until the direction at the bottom of the chart is the same as the direction you are facing.

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STAR CHARTS

NORTHERN HEMISPHERE SKY

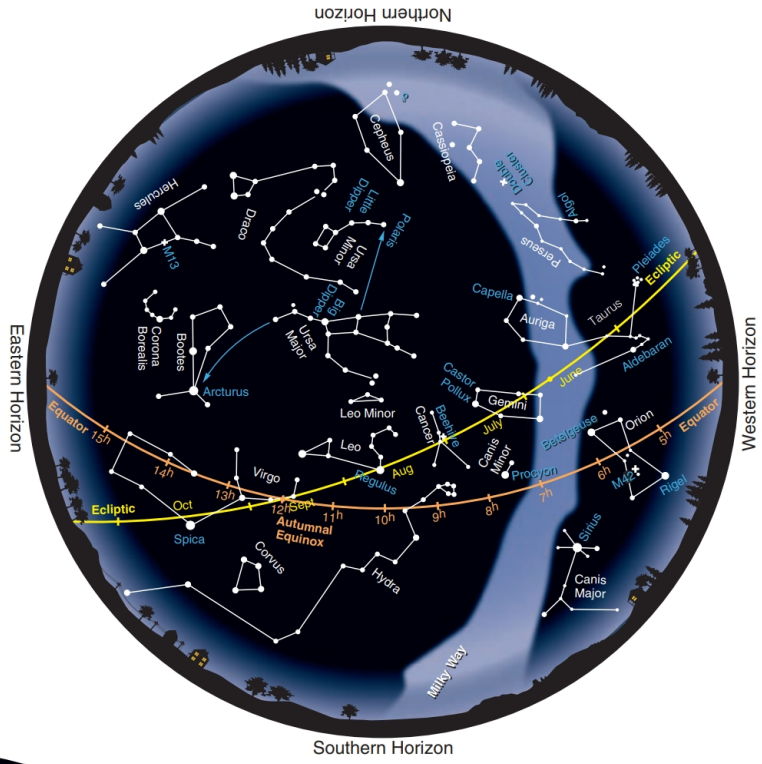
February–March–April

February	midnight
March	10 P.M.
April	8 P.M.

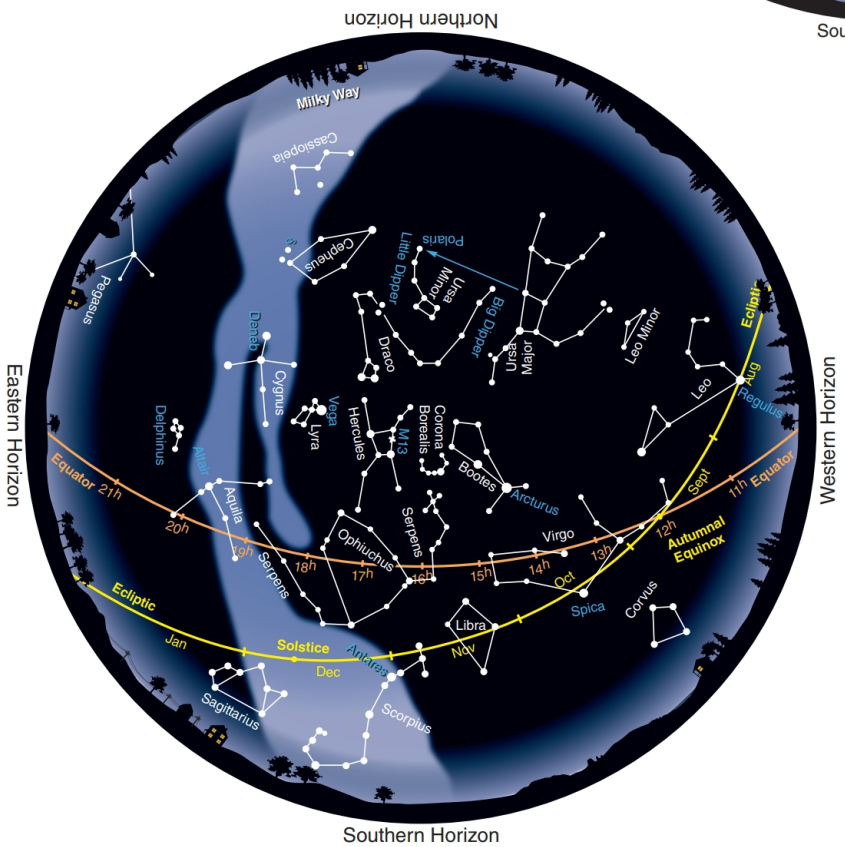
Times are Standard Time; for Daylight Savings Time, add 1 hour.

Months along the ecliptic show the location of the Sun during the year.

Numbers along the celestial equator show right ascension.



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NORTHERN HEMISPHERE SKY

May–June–July

May	midnight
June	10 P.M.
July	8 P.M.

Times are Standard Time; for Daylight Savings Time, add 1 hour.

Months along the ecliptic show the location of the Sun during the year.

Numbers along the celestial equator show right ascension.

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NORTHERN HEMISPHERE SKY

August–September–October

August	midnight
September	10 P.M.
October	8 P.M.

Times are Standard Time; for Daylight Savings Time, add 1 hour.

Months along the ecliptic show the location of the Sun during the year.

Numbers along the celestial equator show right ascension.



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NORTHERN HEMISPHERE SKY

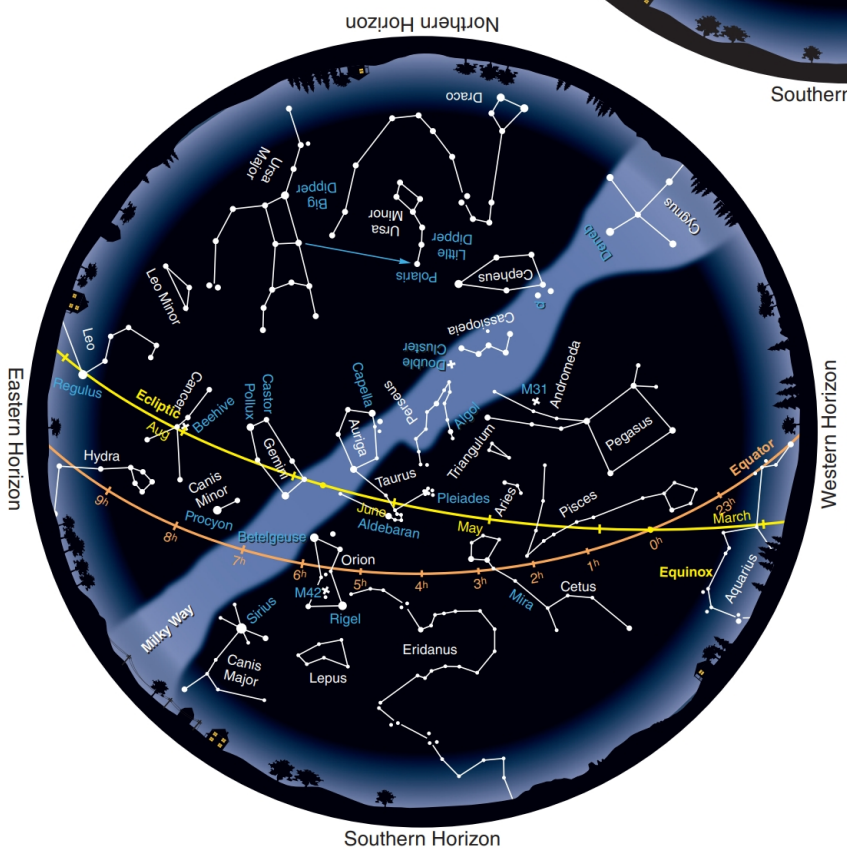
November–December–January

November	midnight
December	10 P.M.
January	8 P.M.

Times are Standard Time; for Daylight Savings Time, add 1 hour.

Months along the ecliptic show the location of the Sun during the year.

Numbers along the celestial equator show right ascension.

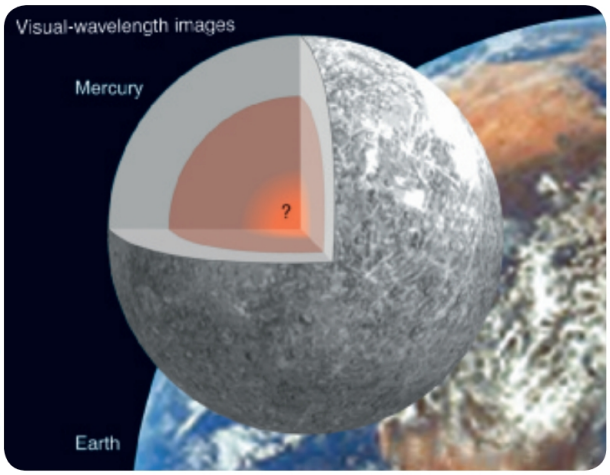


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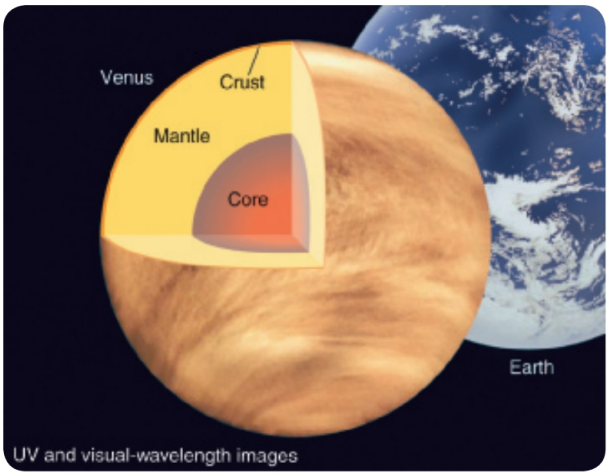
Celestial Profiles

APPENDIX C



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Mercury is slightly more than one-third the diameter of Earth. Its high density must mean it has a large iron core. The amount of heat it retains is unknown.



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Venus's diameter is 95 percent that of Earth. Its atmosphere is perpetually cloudy, and its surface is hot enough to melt lead. Whether it has a liquid metal core like Earth's is currently a matter of conjecture.

Mercury

Motion

Average distance from Sun	0.387 AU (5.79×10^7 km)
Eccentricity of orbit	0.206
Inclination of orbit to ecliptic	7.0°
Orbital period	0.241 y (88.0 d)
Period of rotation (sidereal)	58.65 d
Inclination of equator to orbit	0.0°

Characteristics

Equatorial diameter	4.89×10^3 km (0.383 $D_\oplus$)
Mass	3.30×10^{23} kg (0.0553 $M_\oplus$)
Average density	5.43 g/cm^3 (5.4 g/cm^3 uncompressed)
Surface gravity	0.38 Earth gravity
Escape velocity	4.3 km/s (0.38 $V_\oplus$)
Surface temperature	−170° to 430°C
Average albedo	0.12
Oblateness	0

Historical Point

Mercury lies very close to the Sun and completes an orbit in only 88 Earth days. For this reason, the ancients named the planet after Mercury, the fleet-footed messenger of the gods. The name is also applied to the element mercury, which is known as quicksilver because it is a heavy, quick-flowing silvery liquid at room temperatures.

Venus

Motion

Average distance from Sun	0.723 AU (1.08×10^8 km)
Eccentricity of orbit	0.007
Inclination of orbit to ecliptic	3.4°
Orbital period	0.615 y (224.70 d)
Period of rotation (sidereal)	243.0 d
Inclination of equator to orbit	177.3° (retrograde rotation)

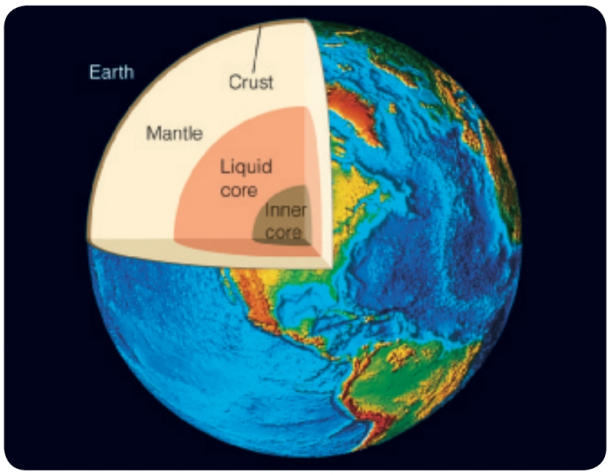
Characteristics

Equatorial diameter	1.21×10^4 km (0.950 $D_\oplus$)
Mass	4.87×10^{24} kg (0.815 $M_\oplus$)
Average density	5.20 g/cm^3 (4.2 g/cm^3 uncompressed)
Surface gravity	0.90 Earth gravity
Escape velocity	10.4 km/s (0.92 $V_\oplus$)
Surface temperature	470°C
Albedo (cloud tops)	0.90
Oblateness	0

Historical Point

Venus is named for the Roman goddess of love, perhaps because the planet often shines so beautifully in the evening or dawn sky. In contrast, the ancient Maya identified Venus as their war god Kukulkan and sacrificed human victims to the planet when it rose in the dawn sky.

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Earth's surface is marked by high continents and low sea floors. The crust is only 10 to 60 km thick. Interior to that are a thick mantle, liquid outer core, and solid inner core.

Earth

Motion

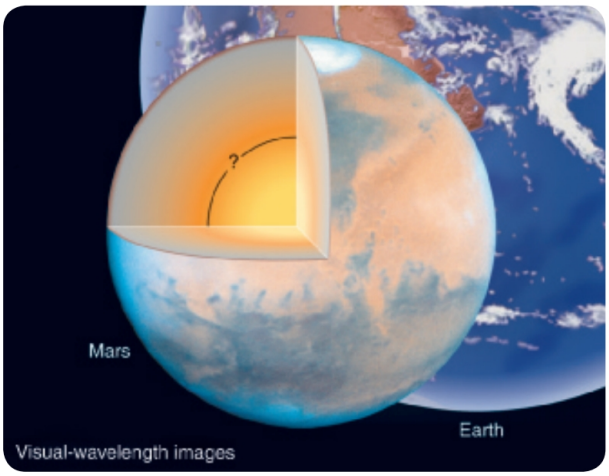
Average distance from Sun	1.00 AU (1.50×10^8 km)
Eccentricity of orbit	0.017
Inclination of orbit to ecliptic	0° (by definition)
Average orbital velocity	29.8 km/s
Orbital period	1.0000 y (365.26 d)
Period of rotation	24.00 h (with respect to Sun)
Period of rotation	23.93 h (with respect to the stars)
Inclination of equator to orbit	23.4°

Characteristics

Equatorial diameter	1.28×10^4 km
Mass	5.97×10^{24} kg
Average density	5.52 g/cm^3 (4.07 g/cm^3 uncompressed)
Surface gravity	1.00 Earth gravity
Escape velocity	11.2 km/s
Surface temperature	−90° to 60°C
Average albedo	0.31
Oblateness	0.0034

Historical Point

The modern English word *Earth* comes from Old English *eorthe* and ultimately from the Indo-European root *er-*, meaning ground or dirt. *Terra* comes from the Roman goddess of fertility and growth: thus, *Terra Mater*, Mother Earth.



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Mars has half the diameter of Earth and probably retains some internal heat, but the size and composition of its core are not well known.

Mars

Motion

Average distance from Sun	1.52 AU (2.28×10^8 km)
Eccentricity of orbit	0.093
Inclination of orbit to ecliptic	1.9°
Orbital period	1.881 y (687.0 d)
Period of rotation (sidereal)	24.62 h
Inclination of equator to orbit	25.2°

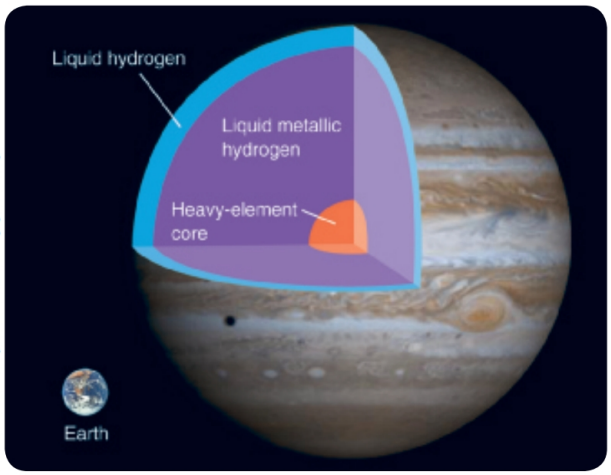
Characteristics

Equatorial diameter	6.79×10^3 km (0.533 $D_\oplus$)
Mass	6.42×10^{25} kg (0.107 $M_\oplus$)
Average density	3.93 g/cm^3 (3.3 g/cm^3 uncompressed)
Surface gravity	0.38 Earth gravity
Escape velocity	5.0 km/s (0.45 $V_\oplus$)
Surface temperature	−140° to 15°C
Average albedo	0.25
Oblateness	0.009

Historical Point

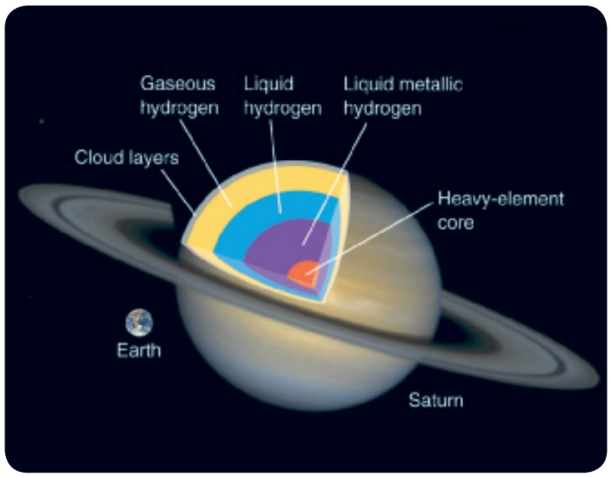
Mars is named for the god of war. Minerva was the goddess of defensive war, but Bullfinch's *Mythology* refers to Mars's "savage love of violence and bloodshed." You can see the planet glowing reddish orange from Earth. Because of iron oxides in its soil, cultures throughout history have associated the red colour of Mars with blood.

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Jupiter is mostly a liquid hydrogen planet with a relatively thin gaseous atmosphere of hydrogen, helium, and hydrocarbons that provide colour to its surface. The cores of all Jovian planets are of unknown composition. It is speculated that Jupiter's core may well be a loose rubble of rock and other compounds.



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Density, oblateness, and gravity measurements made by planetary probes allow planetary astronomers to model Saturn's interior.

Jupiter

Motion

Average distance from Sun	5.20 AU (7.79×10^8 km)
Eccentricity of orbit	0.049
Inclination of orbit to ecliptic	1.3°
Orbital period	11.9 y
Period of rotation	9.92 h
Inclination of equator to orbit	3.1°

Characteristics

Equatorial diameter	1.43×10^5 km (11.2 $D_\oplus$)
Mass	1.90×10^{27} kg (318 $M_\oplus$)
Average density	1.33 g/cm^3
Gravity at cloud tops	2.5 Earth gravities
Escape velocity	59.5 km/s (5.3 $V_\oplus$)
Temperature at cloud tops	145°K
Albedo	0.34
Oblateness	0.065

Historical Point

Jupiter is named for the Roman king of the gods (the Greek Zeus), and it is the largest planet in our solar system. It can be very bright in the night sky, and its cloud belts and four largest moons can be seen through even a small telescope. Its moons are even visible with a good pair of binoculars mounted on a tripod.

Saturn

Motion

Average distance from Sun	9.58 AU (1.43×10^9 km)
Eccentricity of orbit	0.056
Inclination of orbit to ecliptic	2.5°
Orbital period	29.5 y
Period of rotation	10.56 h
Inclination of equator to orbit	26.7°

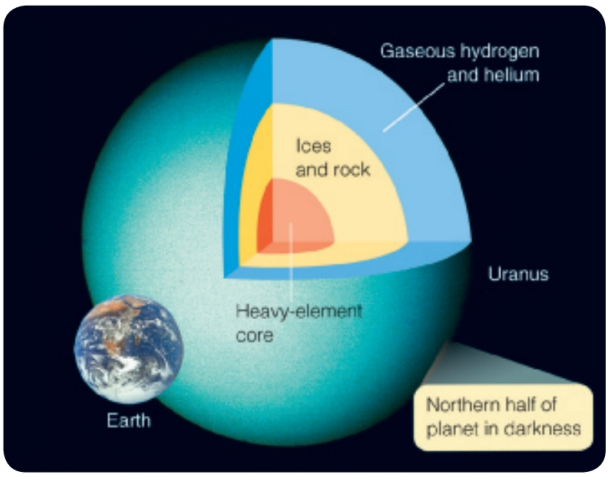
Characteristics

Equatorial diameter	1.21×10^5 km (9.45 $D_\oplus$)
Mass	5.68×10^{26} kg (95.2 $M_\oplus$)
Average density	0.69 g/cm^3
Gravity at cloud tops	1.1 Earth gravities
Escape velocity	35.5 km/s (3.2 $V_\oplus$)
Temperature at cloud tops	95°K
Albedo	0.34
Oblateness	0.098

Historical Point

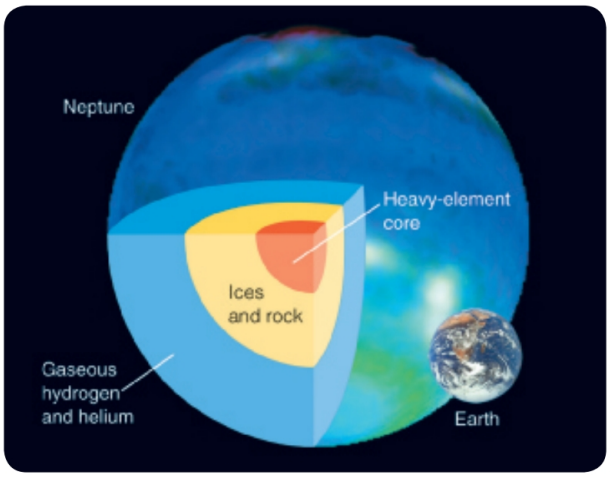
The Greek god Cronus was forced to flee when his son Zeus took power. Cronus went to Italy where the Romans called him Saturn, protector of the sowing of seed. He was celebrated in a week-long Saturnalia festival at the time of the winter solstice in late December. Early Christians took over the holiday to celebrate Christmas.

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Uranus rotates on its side, and, when *Voyager 2* flew past in 1986, the planet's south pole was pointed almost directly at the Sun.



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Neptune was tipped slightly away from the Sun when the Hubble Space Telescope recorded this image. The interior is much like that of Uranus, but Neptune has more heat flowing outward.

Uranus

Motion

Average distance from Sun	19.2 AU (2.88×10^9 km)
Eccentricity of orbit	0.047
Inclination of orbit to ecliptic	0.8°
Orbital period	84.0 y
Period of rotation	17.24 h
Inclination of equator to orbit	97.8° (retrograde rotation)

Characteristics

Equatorial diameter	5.11×10^4 km (4.01 $D_\oplus$)
Mass	8.68×10^{25} kg (14.5 $M_\oplus$)
Average density	1.27 g/cm^3
Gravity	0.9 Earth gravity
Escape velocity	21.3 km/s (1.9 $V_\oplus$)
Temperature at cloud tops	55°K
Albedo	0.30
Oblateness	0.023

Historical Point

Uranus was discovered in 1781 by William Herschel, a German-born scientist who lived and worked most of his life in England. He named the new planet *Georgium Sidus*, meaning "George's Star" in Latin, after the English King George III. European astronomers, especially the French, refused to accept a planet named after an English king. Instead, they called the planet Herschel. Years later, German astronomer J. E. Bode suggested it be named Uranus after the oldest of the Greek gods.

Neptune

Motion

Average distance from Sun	30.1 AU (4.50×10^9 km)
Eccentricity of orbit	0.009
Inclination of orbit to ecliptic	1.8°
Orbital period	164.8 y
Period of rotation	16.11 h
Inclination of equator to orbit	28.3°

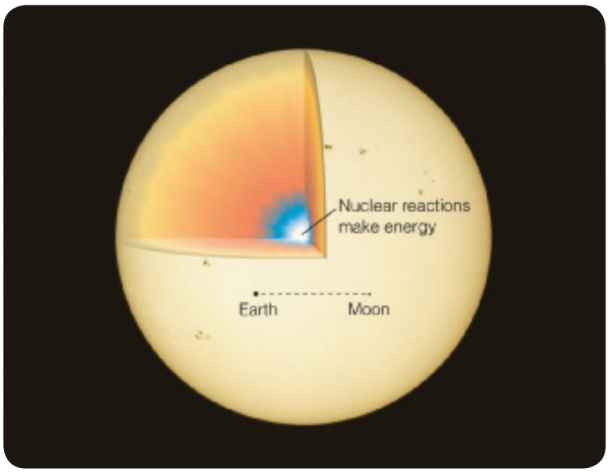
Characteristics

Equatorial diameter	4.95×10^4 km (3.88 $D_\oplus$)
Mass	1.02×10^{26} kg (17.1 $M_\oplus$)
Average density	1.64 g/cm^3
Gravity	1.1 Earth gravities
Escape velocity	23.5 km/s (2.1 $V_\oplus$)
Temperature	55°K
Albedo	0.29
Oblateness	0.017

Historical Point

A British and a French astronomer independently calculated the existence and location of Neptune from its gravitational influence on the motion of Uranus. British observers were too slow to act on this information; Neptune was discovered in 1846, and the French astronomer got the credit. Because of its blue colour, astronomers named Neptune after the god of the sea.

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This visible image of the Sun shows a few sunspots and is cut away to show the location of energy generation at the Sun's centre. The Earth–Moon system is shown for scale.

The Sun

From Earth

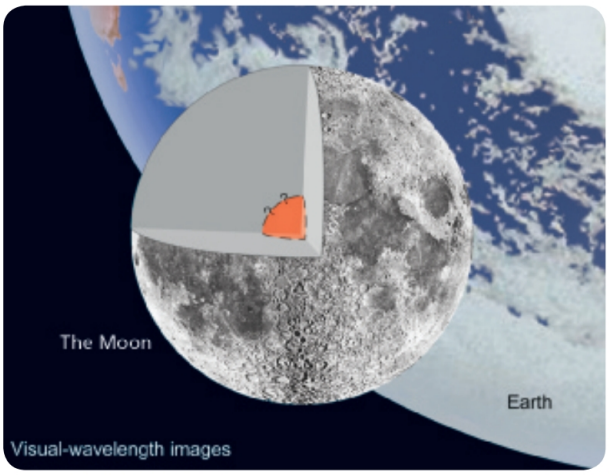
Average distance from Earth	1.000 AU (1.496×10^8 km)
Maximum distance from Earth	1.017 AU (1.521×10^8 km)
Minimum distance from Earth	0.983 AU (1.471×10^8 km)
Equatorial angular diameter	0.533° (1920 arc seconds)
Period of rotation (sidereal)	24.5 days at equator
Apparent visual magnitude	−26.74

Characteristics

Radius	6.96×10^5 km
Mass	1.99×10^{30} kg
Average density	1.41 g/cm^3
Escape velocity at surface	618 km/s
Luminosity	3.84×10^{26} J/s
Surface temperature	5780 K
Central temperature	15.7×10^6 K
Spectral type	G2 V
Absolute visual magnitude	+4.83

Historical Point

In Greek mythology, the Sun was carried across the sky in a golden chariot pulled by powerful horses and guided by the sun god Helios. When Phaeton, the son of Helios, drove the chariot one day, he lost control of the horses, and Earth was nearly set ablaze before Zeus smote Phaeton from the sky. Even in classical times, people understood that life on Earth depends critically on the Sun.



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Earth's moon has about a quarter the diameter of Earth. Its low density indicates that it does not contain much iron. The size of its core, if any, and the amount of remaining heat are unknown.

The Moon

Motion

Average distance from Earth	3.84×10^5 km (centre to centre)
Eccentricity of orbit	0.055
Inclination of orbit to ecliptic	5.1°
Average orbital velocity	1.02 km/s
Orbital period (sidereal)	27.3 d
Orbital period (synodic)	29.5 d
Inclination of equator to orbit	6.7°

Characteristics

Equatorial diameter	3.48×10^3 km ($0.273\ D_\oplus$)
Mass	7.35×10^{22} kg ($0.0123\ M_\oplus$)
Average density	3.35 g/cm^3 (3.3 g/cm^3 uncompressed)
Surface gravity	0.17 Earth gravity
Escape velocity	2.4 km/s ($0.21\ V_\oplus$)
Surface temperature	−170° to 130°C
Average albedo	0.12
Oblateness	0

Historical Point

Lunar superstitions are common. The words *lunatic* and *lunacy* come from *luna*, the moon. Someone who is *moonstruck* is supposed to be a bit nutty. Because the Moon affects the ocean tides, many superstitions link the Moon to water, weather, and women's cycle of fertility. According to legend, moonlight is supposed to be harmful to unborn children, but on the plus side, moonlight rituals are said to remove warts.

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INDEX



3C 175, 246
3C 273, 246
4U 1543-47, 194
47 Tucanae, 174
51 Pegasi, 300, 366

A

A0620-00, 194
A Message from Earth (AMFE), 372
A ring, 347
Aagjuk, 48
Abell 520, 238, 240
Abell 1689, 232
Abell 2281, 237
Abiogenesis, 362
Absolute visual magnitude (MV), 124–125
Absolute zero, 96
Absorption lines, 104
Absorption spectrum, 104
Abu Rayhan Al-Biruni, 54, 201
Acceleration, 63
Acceleration of universe, 267–268
Accretion, 290
Accretion disk, 178
Accuracy of measurements, 79
Active galactic nuclei (AGN), 241
Active galaxy, 241
Active regions, 113
Adams, John Couch, 349
Adaptive optics, 79, 297
Adhara, 132
AGN. *See* Active galactic nuclei (AGN)
Aine Corona, 321
Airborne and space observations, 86–89
  telescopes in space, 87–89
  visual spectrum, 86–87
Aitken Basin, 5, 317
Akatsuki, 322
Akuttujuuk, 48
Al Magisti, 53
Albedo, 314
Albireo, 42
Alcor, 133–134
Aldebaran, 19, 39
Aldrin, Edwin "Buzz," 316
Alexander the Great, 51
Algonquin Radio Observatory (ARO), 140
ALH 84001, 368
ALICE, 258
ALMA. *See* Atacama Large Millimeter/Submillimeter Array (ALMA)
Almagest, 53
Alnilam, 38
Alnitak, 38
Alpha (α), 19
Alpha Centauri, 123
Alpher, Ralph, 255
Alpheratz, 19, 42
Altair, 48, 132
AM radio transmissions, 76
Amalthea, 383
AMFE. *See* A Message from Earth (AMFE)
Amino acids, 360, 362
Anasazi rock painting, 47, 49
Anaxagoras, 201
Ancient times, 46–54
Andromeda Galaxy, 19, 42, 231, 240–241
Angstrom, 75, 379
Angular distance, 23
Angular momentum, 178
Annular eclipse, 33–34
Anorthosite, 314
Ante meridian (a.m.), 37
Antennae Galaxies, 239–240
Antimatter, 260
Antiparticles, 260
Aphelion, 29
Apogee, 67
Apollo 11 Moon landing, 316
Apollo Moon rocks, 315
Apollo program, 316–318
Apparent brightness, 124
Apparent solar time, 37
Apparent visual magnitude (m_v), 20
Arc minutes, 23
Arc seconds, 23
Arcturus, 40
Arecibo anticoded message, 372
Argyre, 324
Ariel, 383
Aristarchus, 51
Aristotle, 50–53, 359
Armstrong, Neil, 316
ARO. *See* Algonquin Radio Observatory (ARO)
Array detector, 84
Arthur B. McDonald Institute, 153
Aryabhatiya (Aryabhata), 51
Asiago DLR Asteroid Survey, 293
Asterism, 19, 40
Asteroid, 280–281
Asteroid Shelton, 185
Astrobiology, 358. *See also* Life in the universe
Astrology, 26
Astronomer's triangulation method, 122–123
Astronomia Nova (Kepler), 57

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Astronomical interferometer, 79
Astronomical navigation (wayfinding), 49
Astronomical systems and techniques
  imaging systems and photometers, 84–85
  spectrographs, 85–86
Astronomical telescopes, 76–86
  adaptive optics, 79
  diffraction fringe, 78
  kinds, 77–78
  light-gathering power, 78
  magnifying power, 80
  primary function, 80
  resolving power, 78
  seeing, 79–80
  space, in, 87–89
  visualizing astronomy, 82
  ways to focus light, 76–77
Astronomical unit (AU), 7, 9, 378–379
Astronomy
  historical overview. *See* Historical overview
  notable Canadians. *See* Canadians in Astronomy
  telescopes. *See* Astronomical telescopes
  timeline, 46, 50–51, 54
Atacama Large Millimeter/Submillimeter Array (ALMA), 5, 83–84
ATLAS, 258–259
Atmospheric window, 76. *See also* Square Kilometre Array (SKA)
Atom, 95, 278
Atom size, 8
Atomic spectra, 104–105
AU. *See* Astronomical unit (AU)
Auriga, 38–39
Aurora, 117
Autumnal equinox, 28
Avempace, 201

B

B ring, 346
Baade, Walter, 185
Babylonians, 47
Balance, 146
Balmer lines, 105–106
Balmer series, 105
Balmer-alpha line, 102
Baltis Vallis, 328
Barberini, Cardinal, 61–62
Barnard 68, 160
Barred spiral galaxies, 227
Baryon, 264
Baryonic matter, 264, 271
Basalt, 310
Baseline, 122
Becklin, Eric, 218
Becklin-Neugebauer object, 165
Beijing Schmidt CCD Asteroid Program, 293
Bell, Jocelyn, 186
Bellarmine, Cardinal, 62
Belt–zone circulation, 338
Bendjoya, Philippe, 293
Benz, Arnold, 115
Beta (ß), 19
Beta Pictoris, 296
Betelgeuse, 19–20, 48, 97, 132
Big bang, 12–13, 251, 254
Big bang theory, 254–262
Big Dipper, 18, 40
Big rip, 269
Binary stars, 132–134. *See also* Binary systems
Binary systems
  commonplace, 132
  evolution, 178–180
  kinds, 133–136
Binding energy, 99
Biographical sketches. *See* Canadians in Astronomy
Biological evolution, 359
Black hole, 188–194
  defined, 190
  event horizon, 191, 194–195
  formation of, 192
  galaxies, 247
  gamma-ray burst, 193–194
  gravitational waves, 195–196
  hypernova, 193
  jets, 193
  leaping into, 191–192
  Milky Way Galaxy, 217, 219
  misconceptions, 191
  radius, 191–192
  Schwarzchild, 190–191
  search for, 192–193
Black hole binaries, 194
Black smokers, 366–367
Blackbody radiation, 95–96, 258
Blackbody spectrum, 157
Blazar, 247
"Blueberries," 326
Blueshift, 102
Bode, J. E., 348
Body cell, 8
Bok, Bart, 164
Bok globule, 163–164
Bolton, Charles Thomas, 235
Bombardment of the planets, 292–293
Bondar, Roberta, 313
Boötes, 40
Boron, 100
Bose, Maitrayee, 5
Bottom-up galaxy formation, 215, 218
Bragg, William Lawrence, 69
Brahe, Tycho, 56
Breccia, 314
Bright giant, 132
Brightest stars, 139, 381
Bright-line spectra, 104
British Columbia, 166
Brown, Mike, 351
Brown dwarf, 127, 154–155
Bruno, Giordano, 304
Bull (Taurus), 38
Burnell, Jocelyn Bell, 4

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C

C ring, 346
Caesar, Julius, 37
Calendars, 37–38
Calibration, 204–205
Callisto, 339, 383
Caloris multiringed basin, 319
Cambrian explosion, 364
Cambrian period, 364–365
Campbell, Bruce, 299
Canada–France–Hawaii telescope (CFHT), 80, 82, 269, 297
Canadian Galactic Plane Survey, 210
Canadian Hydrogen Intensity Mapping Experiment (CHIME), 83–84
Canadians in Astronomy
  Bolton, Charles Thomas, 235
  Bondar, Roberta, 313
  Covington, Arthur Edwin, 140
  Doyon, René, 297
  Freedman, Wendy, 83
  Gladman, Brett J., 337
  Herzberg, Gerhard, 103
  Intuit traditions, 48
  McDonald, Art, 153
  Peebles, Jim, 256
  Plaskett, John Stanley, 207
  Sawyer Hogg, Helen, 41
  Seager, Sara, 366
  Shelton, Ian Keith, 185
Canis Major, 38–39, 138, 233, 240
Canis Minor, 38–39
Cannon, Annie Jump, 126
Capella, 36, 39, 125, 132
Capsule biographies. *See* Canadians in Astronomy
Capture hypothesis, 314
Carbonaceous chondrite, 286
Carbon-based life, 358
Carbon–nitrogen–oxygen (CNO) cycle, 152
Carnegie Supernova Project, 83
Cartwheel Galaxy, 239
Cassegrain focus, 82
Cassegrain telescope, 78
Cassini Division, 346
Cassini spacecraft, 343–345, 347
Cassiopeia, 42
Cassiopeia A (Cas A), 184
Castor, 39
Catalina Sky Survey, 293
Catastrophic theory, 294
CCD. *See* Charge-coupled device (CCD)
Celestial equator, 22, 36
Celestial profiles
  Earth, 388
  Earth's Moon, 391
  Jupiter, 389
  Mars, 388
  Mercury, 387
  Neptune, 390
  Saturn, 389
  Sun, 391
  Uranus, 390
  Venus, 387
Celestial sphere, 21–22
Celsius, Anders, 378
Celsius temperature scale, 378
Centimetre (cm), 8
Central bulge, 206
Centre of mass, 67, 133
Cepheid variable stars, 202, 229
Cepheus, 42
Ceres, 352–353
CERN (Organisation Européenne pour la Recherche Nucléaire), 6–8, 259
CFCs. *See* Chlorofluorocarbons (CFCs)
CFHT. *See* Canada-France-Hawaii telescope (CFHT)
Chained Princess (Andromeda), 42
Chains of inference, 134
Chandra X-ray Observatory, 88
Chandrasekhar, Subrahmanyan, 88, 169, 177
Chandrasekhar limit, 177, 180
Chang'e 4, 5
Charge-coupled device (CCD), 84
Charioteer (Auriga), 39
Charon, 352–353
Chawla, Kalpana, 276
Chicxulub crater, 293
Chlorofluorocarbons (CFCs), 313
Chondrules, 286
Chort, 20
Chromosomes, 361
Chromosphere, 106–108
Circular velocity, 64
Circumpolar constellations, 23
Classification, 225
Closed orbit, 67
Closed universe, 263
Cloud, Preston, 278
cm (centimetre), 8
CMB. *See* Cosmic microwave background (CMB)
CME. *See* Coronal mass ejection (CME)
CMS, 258
CNO (carbon–nitrogen–oxygen) cycle, 152
COBE. *See* Cosmic Background Explorer (COBE)
Cocconi, Giuseppe, 372
Cold dark matter, 265
Colliding galaxies, 237–241
Colours, 75
Coma cluster, 234
Comet, 281, 284–285, 295
Comet Giacobini-Zinner, 285
Comet Halley, 284–285
Comet Shoemaker–Levy 9, 292, 294
Compact object, 177
Comparative planetology, 304
Compton Gamma Ray Observatory, 88, 193
Condensation, 290
Condensation hypothesis, 314
Condensation sequence, 289
Conduction, 147

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Confidence, 60, 118
Confirmation, 118
Conservation laws, 146–147
Conservation of energy, 146–147
Conservation of mass, 146–147
Consolidation, 118
Constellation, 18–19
Constellation boundaries, 18
Contact (Sagan), 357
Continental drift, 311
Continuous spectrum, 104
Convection, 98, 147
Convective zone, 111
Cool stars, 125
Copernican revolution, 57
Copernican universe, 54–56
Copernicus, Nicolaus, 54–55
Corona(e), 107–109, 321
Coronagraph, 108
Coronal hole, 117
Coronal mass ejection (CME), 117
Cosmic Background Explorer (COBE), 272
Cosmic calendar (time), 12–13
Cosmic expansion, 253–254
Cosmic microwave background (CMB), 254–257
Cosmic redshift, 263
Cosmic year, 13
Cosmological constant, 267
Cosmological distance ladder, 229
Cosmological principle, 262
Cosmology, 250–274
  acceleration of universe, 267–268
  big bang, 251, 254
  big bang theory, 254–262
  big rip, 269
  CMB, 254–257
  CMB irregularities, 272–273
  cosmic expansion, 253–254
  cosmic redshift, 263
  cosmological principle, 262
  critical density, 264
  curvature of space-time, 272–273
  dark energy, 267–268
  dark matter, 264–265
  defined, 250
  edge–centre problem, 252
  fate of universe, 269
  first seconds and minutes of universe, 257–260
  flat universe, 263
  flatness problem, 265
  homogeneity, 262
  horizon problem, 265
  Hubble time, 254
  inflation, 265–267
  inflationary big bang, 266
  isotropy, 262
  model universes, 263–264
  observable universe, 253
  Olbers's paradox, 252
  open/closed universe, 263
  origin of structure, 271–272
  recombination, 261
  reionization, 261
Cosmos (Sagan), 354, 358
Coulomb, Charles-Augustin de, 99
Coulomb barrier, 151
Coulomb force, 99, 151
Covington, Arthur Edwin, 140
CP1919, 186
Crab Nebula, 48, 182–183, 186
Crabtree, William, 94
Craters, 282, 292–293
Cretaceous period, end of, 292
Critical density, 264–265, 267
Cubic centimetre, 378
Curiosity, 90, 331–332
Curiosity rover, 323, 327, 330
Curvature of space-time, 272–273
Cygnus, 42, 159
Cygnus Loop, 184
Cygnus X-1, 192, 194, 235

D

Dactyl, 285
Dancing shiva, 259
DAO. *See* Dominion Astrophysical Observatory (DAO)
Dark age, 261
Dark energy, 267–268
Dark halo, 208
Dark matter
  cold, 265
  cosmology, 264–265
  defined, 209
  galaxies, 234–237, 240
Dark nebula, 159
Dark side of the Moon, 30
Dark-line spectra, 104
Darwin, Charles, 225, 359
Darwin's theory of evolution, 60
Dawn, 285, 353
De Revolutionibus Orbium Coelestium (Copernicus), 54–56
Death of stars, 168–197
  black holes, 188–194. *See also* Black hole
  evolution of binary systems, 178–180
  giant stars, 171
  low-mass stars, 173–178
  massive stars, 180–185
  neutron stars, 185–188
  pulsars, 186–188
  red dwarf, 170
  white dwarf, 176–177
Debris disks, 296
Declination, 36
Deep Impact, 285
Deferent, 53
Degenerate matter, 177
Degrees, 23
Deimos, 330, 383
Delta Cephei, 42, 201

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Democritus, 201, 359
Deneb, 42
Density, 95, 378
Density wave theory, 210–211
Deoxyribonucleic acid (DNA), 6, 358, 360–361
Deuterium, 151–152
Dialogo Sopra i Due Massimi Sistemi del Mondo (Galileo), 62
Dicke, Robert, 255
Differential rotation, 111, 205
Differentiation, 290, 313
Diffraction fringe, 78
Digitized, 84
Dione, 383
Direct imaging, 297
Discovery Rupes, 319
Disk component, 205
Disk population stars, 212
Disk stars, 206
Disk-shaped galaxy, 224
Distance ladder, 228–231
DNA. *See* Deoxyribonucleic acid (DNA)
Dog Star (Sirius), 39
Dominion Astrophysical Observatory (DAO), 207
Doppler effect, 101–103
Doppler method, 299
Doyon, René, 297
Drake, Frank, 371–373
Drake equation, 373
Duhalde, Oscar, 183, 185
Dwarf planets, 351–354
  Ceres, 352–353
  defined, 351
  Eris, 353
  Haumea, 353
  Makemake, 353–354
  Pluto, 351–352
Dynamo effect, 111, 309
Dysnomia, 354

E

Eagle Nebula, 160
Early astronomical calendar, 47
Earth, 308–314
  atmosphere, 309–313
  celestial profile, 388
  core, 306–307
  craters, 282, 292–293
  crust, 306–307
  death of, 177–178
  earthquakes, 308, 311
  geological history, 313–314
  global warming, 312
  greenhouse effect, 309, 312
  mantle, 306–307, 309
  Moon. *See* Earth's Moon
  oxygen, 313
  ozone, 313
  plate tectonics, 310–311
  visualizing astronomy, 310–311
  volcanoes, 323–324
  water world, 307
Earthquakes, 308, 311
Earth's Moon, 27–32, 307, 314–318
  Apollo program, 316–318
  celestial profile, 391
  crust, 315
  geology, 314
  history, 315–316
  human spaceflight, 316–318
  large-impact hypothesis, 315–316
  near side/far side, 317
  one-plate planet, 316
  origin, 314–315
  phases, 27, 30–31
East point, 22
e-CALLISTO network, 115
e-CALLISTO spectrometer, 115
Eccentricity *(e),* 58
Eclipse
  annular, 33–34
  lunar, 33–36
  partial, 33
  solar, 17, 32–33
  total, 32, 34
Eclipsing binary system, 136
Ecliptic, 26
Eddington, Arthur, 237
Edge–centre problem, 252
"Edge-on," 298
Einasto, Jaan, 235
Einstein, Albert, 45, 188–189, 235, 238, 267
Einstein's theories, 60
Ejecta, 314
Electromagnetic radiation, 74, 76
Electromagnetic spectrum, 75–76
Electron, 95
Elementary particles, 6
Element-building cycle, 213–214
Ellipse, 57–58
Elliptical galaxies, 226, 233, 241
Emission lines, 104
Emission nebula, 158
Emission spectrum, 104
Empirical, 59
En Hedu'Anna, 47
Enceladus, 348, 383
Encke Gap, 346–347
End of Cretaceous period, 292
Energy, 308
Energy level, 100
Energy transport, 146–147
Enzymes, 360
Epicycle, 53
Equant, 53
Eratosthenes, 50
Eris, 284, 353
Eros (asteroid), 281
Escape velocity, 67, 188
Eta Carinae, 181

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Europa, 339, 366, 383
European INTEGRAL satellite, 88
European Southern Observatory, 219
Event horizon, 191, 194–195
Event Horizon Telescope (EHT), 5, 83–84, 194
Evolutionary theory, 294
Evpatoria Planetary Radar, 372
Excitation of atoms, 100–101
Excited atom, 100
Exoplanets
  atmosphere of, 366
  definition of, 297
  detection of, 298–299
  Doppler method for detecting, 299
  transit method for detecting, 298–299
Extrasolar planet. *See* Exoplanets
Eyepiece, 77

F

F ring, 347
Fahrenheit, Gabriel Daniel, 378
Fahrenheit temperature scale, 378
False-colour image, 85
Far-infrared, 86
FAST. *See* Five-hundred-meter Aperture Spherical Telescope (FAST)
Fermi, Enrico, 88
Fermi Gamma ray–Space Telescope, 88
Field of view, 6
Filament, 108
Filtergram, 108
Finlay-Freundlich, Erwin, 237
First Nations, 166
First principle, 50
First-quarter moon, 30
Fission hypothesis, 314
Five-hundred-meter Aperture Spherical Telescope (FAST), 83
Flares, 117
Flat universe, 263
Flatness problem, 265
Fleming, Sanford, 38
Fleming, Williamina, 126
Flux, 20, 124
Focal length, 77
Foci, 57–58
Folded mountain ranges, 310
Forward scattering, 338
Fossils, 359, 364
Four laws of stellar structure, 146–148
Fraunhofer, Joseph von, 94
Freedman, Wendy, 83
Freeman, Kenneth, 235
Full moon, 30, 32

G

Galactic cannibalism, 240
Galactic ecosystem, 210
Galactic nucleus, 218–219
Galaxias kuklos, 200
Galaxies, 222–249
  active, 241
  black holes, 247
  blazars, 248
  classification, 226–227
  clusters, 232
  collisions, 237–241
  dark matter, 234–237, 240
  defined, 10
  distance, 228–231
  distance ladder, 228–231
  elliptical, 226, 233, 241
  evolution, 237–241
  GOODS research, 225
  Hubble law, 231
  interactions, 237–241
  look-back time, 231
  luminosity, 231
  mass, 233–234
  mergers, 239
  Milky Way. *See* Milky Way Galaxy
  organization of, 232–233
  quasars, 245–247
  radio, 241
  ring, 239
  Seyfert, 242
  spiral, 206, 210–211, 227, 230, 241
  Tully-Fisher relationship, 230
  unified model, 247
Gale Crater, 323, 331
Galilean moons, 339
Galilei, Galileo, 59–62, 93, 110
Galileo spacecraft, 285, 339, 343
Gamma rays, 76
Gamma-ray burst, 193–194
Gamma-ray observatories, 88
Gamow, George, 255
Ganymede, 339, 383
Gas giants, 337
Gemini, 38
Gene, 361
General theory of relativity, 189, 198, 235, 267
Genetic theory of inheritance, 68
Geocentric model of universe, 49–54
Geosynchronous satellite, 66
Gianotti, Fabiola, 5, 251
Giant elliptical galaxy, 232
Giant Magellan Telescope Organization, 83
Giant star, 131, 137, 170
Gigametre, 8
Gladman, Brett J., 337
Gliese 581, 372
Global Oscillation Network Group (GONG), 111
Global warming, 312
Globular cluster, 174, 203–204, 212
Globular cluster H–R diagram, 175
GONG. *See* Global Oscillation Network Group (GONG)
GOODS. *See* Great Observatories Origins Deep Survey (GOODS)
Gram, 378

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Gran Telescopio Canarias (GTC), 81
Grand Canyon, 311
Granulation, 98–99
Granules, 98–99
Grating, 85
Gravitational collapse, 290–291
Gravitational lensing, 235–236, 239
Gravitational redshift, 191
Gravitational waves, 195–196
Gravity, 64, 132
Great Bear (Ursa Major), 19, 40
Great chain of origins, 278–279
Great Dark Spot, 349
Great Dog (Canis Major), 38. *See also* Canis Major
Great Nebula of Orion, 39, 164–165
Great Observatories Origins Deep Survey (GOODS), 225
Great Red Spot, 283, 340
Great Rift, 159
Great Square of Pegasus, 18, 42
Greenhouse effect, 309, 312
Gregorian calendar, 38
Gregory XIII (Pope), 38
GRO J1655-40, 194
Ground state, 101
GTC. *See* Gran Telescopio Canarias (GTC)
Guest star (1054 ce), 182
GW170817, 196

H

H. *See* Hubble constant (H)
H_α Balmer line, 108
H_α filtergram, 108
Habitable zone, 369
Haldane, John, 362
Half-life, 287–288
Halley, Edmund, 94
Halley's Comet, 285–286
Halo population stars, 212
Halo stars, 206
Harmonice Mundi (Kepler), 57
Haumea, 353
Hawking, Stephen, 199
Hayabusa, 5
Heat, 96
Heat flow, 307
Heat of formation, 295
Heavy bombardment, 292
Heliocentric universe, 54–55
Helioseismology, 111
Helium, 100
Helium fusion, 171–173
Helium lines, 127
Helix Nebula, 169
Hellas, 324
Herbig–Haro object, 163
Hercules, 39
Herdsman (Boötes), 40
Herschel, Caroline, 201
Herschel, William, 75, 201, 348
Herschel telescope, 88
Hertzsprung, Ejnar, 129
Hertzsprung–Russell (H–R) diagram, 129–131, 172
Herzberg, Gerhard, 103
Herzberg Canada Gold Medal, 103
Hewish, Anthony, 186
HH 24, 163
Higgs, Peter, 259
Higgs boson, 6, 8, 259
High-density stars, 138
High-energy astrophysics, 88
High-luminosity star, 369
High-redshift quasar, 247
Himalia, 383
Hipparchus, 19–20
Hipparcos satellite, 123, 132
Historical overview, 44–70
  ancient times, 46–54
  Brahe, 56
  Copernican universe, 54–56
  Copernicus, 54–55
  Galileo, 59–62
  geocentric model of universe, 49–54
  heliocentric universe, 54–55
  Kepler, 57–59
  Kepler's laws of planetary motion, 57–59, 64–65
  Newton, 62–65
  Newton's laws of motion, 62–63
  Ptolemaic universe, 51, 53
  timeline, 46, 50–51, 54
  universal theory of gravitation, 63–64
HII regions, 158
Homogeneity, 262
Hope Mars Mission, 330
Horizon problem, 265
Horizontal branch, 172
Horock, Jeremiah, 94
Horsehead Nebula, 156
Hot spots, 310
Hot stars, 125
House of Wisdom (Baghdad), 51
How Do We Know? boxes
  accuracy of measurements, 79
  astronomical navigation (wayfinding), 49
  calibration, 205
  chains of inference, 134
  classification, 225
  confirmation, confidence, and consolidation, 118
  energy, 308
  hypothesis, theory, and law, 60
  mathematical models, 149
  present is key to past, 327
  pseudoscience, 26
  scientific method, 11–12
  scientific model, 21
  scientific predictions, 68
  scientific revolutions, 57
  scientists (nature's detectives), 301
  selection effects, 228
  statistical evidence, 245

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theories and proof, 190
UFOs and space aliens, 371
HR 8799, 297
H–R diagram, 129–131, 172
HST. *See* Hubble Space Telescope (HST)
Hubble, Edwin P., 83, 87, 205, 224, 231, 253, 267
Hubble constant (H), 83, 231
Hubble Deep Field, 225
Hubble law, 231, 246
Hubble Legacy Field, 225, 237
Hubble Space Telescope (HST), 83, 87, 225, 229, 237
Hubble time, 254
Huygens probe, 345
Hyabusa 2, 285
Hyades cluster, 39, 174
Hydra, 253, 354
Hydrogen, 101
Hydrogen Balmer lines, 125, 128, 131
Hydrogen-fusion shell, 171
Hydrostatic equilibrium, 146, 148
Hypatia, 51
Hyperion, 383
Hypernova, 193
Hypernova explosion, 193
Hypothesis, 11, 60, 190

I

Iapetus, 383
Ibn Qayyim Al-Jawziyya, 201
ICE. *See International Cometary Explorer* (ICE) spacecraft
Ice giants, 337
Ice line, 289
Imaging systems and photometers, 84–85
Impact craters, 282, 292–293
Indigenous peoples, 166
Inflation, 265–267
Inflationary big bang, 266
Infrared (IR), 75
Instability strip, 202
INTEGRAL satellite, 88
Interferometer, 78–79
International Astronomical Union (IAU), 18, 350
International Cometary Explorer (ICE) spacecraft, 285
International System of Units, 378
Interstellar dust, 157
Interstellar medium (ISM), 157, 160–162
Interstellar reddening, 157, 160
Intrinsic brightness, 124
Intuit traditions, 48
Inverse square relation, 64, 124
Io, 342, 383
Ion, 99
Ionization, 99
Iridium, 292
Iron meteorite, 286
Irregular galaxies, 226, 232
Ishtar Terra, 320
ISM. *See* Interstellar medium (ISM)
Isotopes, 100
Isotropy, 262
Itokawa, 5

J

James Webb Space Telescope (JWST), 87
Janus, 383
Japan Spaceguard Association, 293
Jets, 193, 247
John Paul II (Pope), 62
Jones, Albert, 185
Jovian planets, 280, 282–283, 334–355
atmospheres and interiors, 337
massive, low-density worlds, 295
Neptune, 348–350
planetary rings, 295
Uranus, 348–351
visualizing astronomy, 282–283
Julian calendar, 37
Jupiter, 337–343
atmosphere, 337–338, 340–341
celestial profile, 389
core, 338
interior, 337–338
moons, 339–342
principal satellites, 383
rings, 338–339
visualizing astronomy, 340–341
Jupiter Icy Moon Explorer (JUICE), 343
JWST. *See* James Webb Space Telescope (JWST)

K

K-Pg boundary, 292
K-T boundary, 292
K star, 300
Kajita, Takaaki, 153
Kaku, Michio, 145
KELT-9b, 301
Kelvin temperature scale, 96, 378
Kepler, Johannes, 57–59, 94
Kepler Mission, 87
Kepler satellite, 88
Kepler space telescope, 298
Kepler-62, 300
Kepler-1625b, 300
Kepler's laws of planetary motion, 57–59, 64
Kepler's supernova, 183
Kerberos, 354
Kids, 39
Kilometre (km), 8
Kilonovae, 196
Kiloparsec (kpc), 379
King (Cepheus), 42
Kirchhoff, Gustav, 104
Kirchhoff's laws, 104
Kleinmann-Low Nebula, 165
km (kilometre), 8
Kuiper, Gerard, 284
Kuiper belt, 284, 351

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L

L dwarf, 127
Lafrienière, David, 297
Lakshmi Planum, 320
Landing on the Moon, 316–318
Large Hadron Collider (LHC), 4, 6–7, 258–259
Large Magellanic Cloud, 183
Large-impact hypothesis, 315–316
Large-scale structure, 271
Laser Interferometer Gravitational Wave Observatory (LIGO), 270
Late heavy bombardment, 316
Law of conservation of energy, 146–147
Law of conservation of mass, 146–147
Law of energy transport, 146–147
Laws, 60
Laws of stellar structure, 146–148
Le Verrier, Urbain, 349
Leap year, 37
Leavitt, Henrietta, 202
Leo, 40
Levy, David, 293
LHC. *See* Large Hadron Collider (LHC)
LHCb, 258
Life in the universe, 356
  biological evolution, 359
  DNA, 358, 360–361
  evolution of life, 364–365
  life in other planetary systems, 368–370
  life in our solar system, 365–368
  origin of life on Earth, 359–364
  physical basis of life, 358
  search for extraterrestrial intelligence, 371–373
  travel between stars, 370
Light, 74
Light curve, 136
Light-gathering power, 78
Lighthouse model, 186
Light-year (ly), 10, 123, 379
Liquid giants, 337
Liquid metallic hydrogen, 337
Little Bear (Ursa Minor), 40
Little Dog (Canis Minor), 38
Little Ice Age, 113
LMC X-3, 194
Lobate scarp, 319
Local Group, 9–10, 232–233
Local meridian, 37
Local Supercluster, 271
Longer-wavelength photons, 76
Look-back time, 231, 241
Lorentz, Hendrik, 1888
Lower-main-sequence M stars, 138
Low-luminosity star, 369
Low-mass stars, 154
Luminosity class, 132
Luminosity (L)
  defined, 125
  galaxies, 231
  mass–luminosity relation, 137, 154
  period–luminosity relation, 203
  stars, 124–125, 129–132
Luminosity spectral classification, 131–132
Luminous stars, 139
Luminous supergiant, 132
Lunar eclipse, 33–36
Lunar geology, 314
Lunar standstill, 47
ly (light-year), 10, 123, 379
Lyman lines, 105
Lyman series, 105

M

M stars, 127, 138
M1, 39
M2, 39
M2-9, 176
M42, 38
M67, 175
M87, 226
Magellanic Clouds, 89, 226
Magma ocean, 315
Magnetar, 186
Magnetic carpet, 109
Magnetic solar phenomena, 116–117
Magnetosphere, 338, 340–341
Magnifying power, 80
Magnitude scale, 19–20
Main-sequence stars, 154–156
  aging, 155–156
  brown dwarfs, 154–155
  defined, 131
  density, 137
  H–R diagram, 131
  luminosity, 132, 154
  properties, 380
  properties of, 156
Mainstream fitting, 228
Makemake, 353–354
Mangalyaan, 5
Manicouagan crater, 292
Manilius, 201
Mantle, 306–307, 309
Mare Crisium, 317
Mare Imbrium, 317
Mare Serenitatis, 317
Maria, 314, 317
Mariner 4, 330
Mariner 10 spacecraft, 318–319
Marois, Christian, 297
Mars, 307, 322–327, 329–331
  atmosphere, 322–323
  celestial profile, 388
  distance from earth, 7
  history, 327, 330
  moons, 330–331
  principal satellites, 383
  red desert planet, 326
  runaway refrigerator, 329

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surface, 323–324
water, 324–327
Mars 2020 rover, 330
Mars Global Surveyor, 325
Mars Odyssey, 325–326
Mars Orbiter Mission (MOM), 5
Mars Pathfinder, 330
Mars Reconnaissance Orbiter, 325
Mass, 64
Mass transfer, 178
Massive compact halo objects (MACHOS), 209
Massive stars, 156
Mass–luminosity relation, 137, 154
Mathematical equations, 11–12
Mathematical models, 149
Mathematical Syntaxis (Ptolemy), 53
Mather, John, 272
Mathilde (asteroid), 281
Mauna Kea, Hawaii, 86
Mauna Loa, 323
Maunder, E. Walter, 112
Maunder butterfly diagram, 112
Maunder minimum, 113
Maxwell Montes, 320
Mayans, 47
Mayor, Michel, 300
McDonald, Art, 153
McKellar, Andrew, 255
Measurements, 79
Medium-mass sunlike stars, 173
Megametre, 8
Megaparsec (Mpc), 229, 379
Mendel, Gregor, 11
Mercury, 282, 307
celestial profile, 387
history, 318
human spacecraft, 316–318
orbital period, 318
size, 7
solar day, 318
MESSENGER spacecraft, 283, 318
Messier, Charles, 38
Messier objects, 39
Metal, 212
Meteor, 285
Meteor shower, 286
Meteorite, 286
Meteoroid, 285
Metric system, 378
Mice Galaxies, 238
Michelson, Albert A., 189
Micrometeorite, 316
Micrometre (μm), 8
Microwave transmissions, 76
Mid-ocean rise, 310
Milky Way, 8, 10
Milky Way Galaxy, 198–220
age, 212
artist's conception, 206
black hole, 217, 219
bottom-up hypothesis, 215, 218
central bulge, 206
dark halo, 208
defined, 10
disk component, 205
Drake equation, 373
galaxy interactions, 238, 240
globular clusters, 204
habitable zone, 369
halo, 206
nucleus, 218–219
population I/II stars, 212
SgrA*, 216–219
size, 202–203, 332
spherical component, 206
top-down hypothesis, 214
Miller, Stanley, 362
Miller-Urey experiment, 362–363
Millimetre (mm), 8
Mimas, 383
Mintaka, 38
Miranda, 349–350, 383
Mizar, 133–134
mm (millimetre), 8
Model universes, 263–264
Molecular cloud, 161
Molecule, 96
Monolithic collapse model, 214–215
Monstein, Christian, 115
Moon phases, 27, 30–31
Moons, 383
Earth. *See* Earth's Moon
Jupiter, 339–342
Mars, 330–331
Neptune, 349–350
Pluto, 351–352
Saturn, 347
trans-Neptunian objects (TNOs), 354
Morley, Edward W., 189
Morphological galaxy classification, 226
Morrison, Philip, 372
Mount Sharp, 323
Mpc (megaparsec), 229
MU_{69}, 352
Multicellular, 364
Multiringed basin, 316
μm (micrometre), 8
Murchison meteorite, 363

N

Nadir, 22
Namaka, 354
Nanometre (nm), 8, 75
National Aeronautics and Space Administration (NASA), 5
National Radio Astronomy Observatory, 83
Natural law, 60
Natural selection, 359
NCG 2998, 234
Neap tides, 68

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Near Earth Asteroid Rendezvous (NEAR) spacecraft, 281
NEAR Shoemaker, 285
Near-Earth Asteroid Tracking (NEAT), 293
Near-Earth object (NEO), 293
Nearest stars, 139, 380
Near-infrared, 86
Near-ultraviolet, 86
NEAT. *See* Near-Earth Asteroid Tracking (NEAT)
Nebula, 157–159
Nebula N44, 156
NEO. *See* Near-Earth object (NEO)
Neon signs/colours, 101
Neptune, 348–350, 383, 390
Nereid, 350, 383
Neutrino, 151–153
Neutron, 95
Neutron star, 185–188
Neutron star mergers, 196
New Horizons spacecraft, 351–352, 370
New moon, 30, 32
Newton, Isaac, 62–65, 85, 235
Newtonian focus, 81
Newton's laws of motion, 60, 62–63
Newton's universal law of gravitation, 60, 63–64
NGC 891, 84
NGC 1365, 227
NGC 1999, 164
NGC 2264, 175
NGC 4038, 240
NGC 4039, 240
NGC 4755, 121
Night sky tours, 38–42
Nix, 354
nm (nanometre), 8
Nonbaryonic matter, 264
North celestial pole, 22–23
North point, 22
Northern Gemini telescope, 74
Northern hemisphere sky, 39, 41, 385–386
Notable Canadians. *See* Canadians in Astronomy
Nova, 170, 178–179
Nova explosion, 180
Nuclear fission, 150
Nuclear forces, 150
Nuclear fusion, 150–154, 180–181
Nuclear power plants, 150
Nucleosynthesis, 257
Nucleus, 95
Nuuttuittuq, 48

O

O stars, 126
Oberon, 383
Observable universe, 253
Observing the sky, 38–42, 384–386
Ocampo, Adriana, 292, 335
Olbers, Heinrich, 252
Olbers's paradox, 252
Olympus Mons, 323–324, 329–330
Ontario Lacus, 345
Oort, Jan, 285
Oort cloud, 284–285
Opacity, 147
Oparin, Alexander, 362
Open cluster, 174, 203, 212
Open orbit, 67
Open universe, 263
Opportunity rover, 326, 330
Optical astronomers, 83
Optical telescope, 78
Orbital motion, 64–65
Orbiting Earth, 66–67
Orcus, 284, 354
Origin of structure, 271–272
Orion Nebula, 20, 38, 164–165
Outer solar system
  dwarf planets, 351–354
  Jovian planets. *See* Jovian planets
Outflow channel, 325–326
Outgassing, 290–291
Overlapping diffraction fringes, 78
Ovoid, 349–350
Ozma, 371
Ozone, 313

P

Paleolithic cave paintings, 46
Pangaea, 311
Panspermia, 337, 364
Paradigm, 57
Parallax, 52
Parallax catalogues, 123
"Parked car effect," 312
Parkes Observatory telescope, 77
Parsec (pc), 123, 379
Paschen lines, 105
Paschen series, 105
Payne-Gaposchkin, Cecilia, 106–107, 145
pc (parsec), 123, 379
Peebles, Jim, 235, 256
Pegasus, 19, 42
Penumbra, 32
Penzias, Arno, 254–255
Perigee, 67
Perihelion, 29
Period–luminosity diagram, 203–204
Period–luminosity relation, 203
Perlmutter, Saul, 267
Permafrost, 322
Permitted orbit, 100
Perseid meteor shower, 286
Philae lander, 285
Phobos, 330, 383
Phoebe, 383
Phoenix space probe, 326
Photometer, 84
Photon, 76
Photon wavelength, 100

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Photosphere, 97–98, 111–113
Photosynthesis, 118, 313
Piazzi, Giuseppe, 352
Pickering, Edward, 126
Planck constant, 378
Planck length, 6, 8
Planck space telescope, 272
Planet(s)
  defined, 7
  dwarf, 351–354
  Jovian. *See* Jovian planets
  orbital properties, 382
  physical properties, 382
  revolution of, 279–280
  rotation of, 279–280
  terrestrial. *See* Terrestrial planets
Planetary nebula, 173, 176
Planetary rings, 295
Planetesimal, 290
Plaskett, H. H., 207
Plaskett, John Stanley, 207
Plaskett Medal, 207
Plaskett (Minor Planet No 2905), 207
Plaskett Telescope, 207
Plaskett's Star, 207
Plate tectonics, 310–311
Plates, 310
Plato, 52, 359
Pleiades, 39, 48, 159, 175
Pluto, 351–352
Poe, Edgar Allan, 253
Polaris, 48, 132, 203
Pollux, 39
Poor galaxy cluster, 232
Population I star, 212
Population II star, 212
Positron, 151–152
Post meridian (p.m.), 37
Precession, 24
Pre-Copernicus geocentric paradigm, 57. *See also* Geocentric model of universe
Predictions, 68
Present is key to past, 327
Pressure–temperature thermostat, 154
Primary atmosphere, 309
Primary lens, 77
Primary mirror, 77
Prime focus, 82
Primordial soup, 362
Principa (Newton), 62
Principle of hydrostatic equilibrium, 146, 148
Prism, 85
Prominence, 116
Proper motion, 203
Proteins, 360
Proteus, 383
Proton, 95
Proton–proton chain, 151–152
Protoplanet, 290–292
Protostar, 162–163
Proxima Centauri, 10
Proxima Centauri b, 301
Pseudoscience, 26
Ptolemaic universe, 51, 53
Ptolemy, Claudius, 19, 50–51, 53
Pulsar, 186–188
Pwyll, 342
Pythagoras, 50

Q

QSO. *See* Quasi-stellar object (QSO)
Qualitative galaxy classification, 226
Quantitative galaxy classification, 227
Quantitative thinking, 379
Quantum leaps, 101
Quantum mechanics, 99
Quaoar, 354
Quasar, 245–247
Quasar eruptions, 247
Quasar redshift, 247
Quasi-stellar object (QSO), 245
Queen (Cassiopeia), 42
Queloz, Didier, 300
Quiescent prominence, 116
Quintessence, 267
QZ Vul, 194

R

RA. *See* Right ascension (RA)
Radial velocity method, 299
Radial velocity (V_r), 102
Radiation, 147
Radio astronomers, 83
Radio communication, 370–372
Radio dish, 83
Radio energy map, 85
Radio galaxy, 242
Radio interference, 84
Radio telescope, 77–78, 210
Radio waves, 76
Rainbow, 75
Recombination, 261
Reconnections, 117
Red, 75
Red dwarf, 131, 138, 156, 170, 301
Red giant, 171
Red-hot, 95
Redshift, 102
Reflecting telescope, 77
Reflection nebula, 158
Refracting telescope, 77
Regular supergiant, 132
Regulus, 39
Reionization, 261
Resolving power, 79
Retrograde motion, 52, 55
Revolution, 25
Revolution of planets, 279–280

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Rhea, 383
Rheasilvia impact basin, 281
Ribonucleic acid (RNA), 361
Rich galaxy cluster, 232
Riess, Adam, 267
Rigel, 20, 39, 97, 132
Right ascension (RA), 36
Ring galaxy, 239
Ring Nebula, 176
Ring of Fire, 311
Ring systems, 295
RNA. *See* Ribonucleic acid (RNA)
Roche limit, 338
Roche lobe, 178
Roll, Peter, 255–256
Rosalind Franklin, 330
Rotation, 25
Rotation curve, 208–209
Rotation curve method, 233
Rotation of planets, 279–280
Rubin, Vera, 223, 235
Runaway greenhouse effect, 319, 328
Runoff channel, 325
Russell, Henry Norris, 129

S

Sa galaxy, 227
Sagan, Carl, 12, 73, 354, 357–358, 372
Sagittarius A* (SgrA*), 216–219
Sagittarius Dwarf Galaxy (Sgr Dwarf), 233
Sakiattiak, 48
Sakigake, 285
San Andreas fault, 134
Sapas Mons, 320
Saros cycle, 35
Saturn, 343–347
  celestial profile, 389
  moons, 347
  principal satellite, 384
  rings, 344, 346–347
Sawyer Hogg, Helen, 41
Sawyer Hogg (asteroid), 41
Sb galaxy, 227
Sc galaxy, 227
Schmidt, Brian, 267
Schmidt, Maarten, 245
Schmidt–Cassegrain focus, 82
Schwarzchild, Karl, 191
Schwarzchild black hole, 190–191
Schwarzchild radius (R_S), 191–192
Scientific method, 11–12
Scientific model, 21
Scientific notation, 6, 8
Scientific paradigm, 57
Scientific predictions, 68
Scientific revolutions, 57
Scientific theory, 190
Scientists (nature's detectives), 301
SDSS (Sloan Digital Sky Survey), 9–10
Seager, Sara, 366
"Searching for Interstellar Communications" (Cocconi/Morrison), 372
Seasons, 26–27
Secondary atmosphere, 309
Secondary mirror, 77, 82
Sedna, 284, 354
Seeing, 79–80
Selection effects, 228
Self-sustaining star formation, 212
Semi-major axis *(a),* 58
SETI (search for extraterrestrial intelligence), 371–373
Seven Sisters (Pleiades), 39
Seyfert, Carl K., 242
Seyfert galaxies, 242
SgrA*. *See* Sagittarius A* (SgrA*)
Shapley, Harlow, 203, 218
Shell, 171
Shelton, Ian, 183, 185
Shepherd satellites, 347
Shield volcano, 323
Shock wave, 161, 180, 182
Shoemaker, Carolyn and Eugene, 293
Shooting stars, 285
Shorter-wavelength photons, 76
SI units, 378
Sidereal day, 37
Sidereal month, 37
Sidereal tracking, 81
Sidereal year, 37
Sidereus Nuncius (Galileo), 60–61
Silicon, 358
Singularity, 190, 192
Singuuriq, 48
Sirius, 19–20, 39, 47–48, 176
Sirius A, 139, 177
Sirius B, 139, 177
SKA. *See* Square Kilometre Array (SKA)
Skepticism, 301
Sloan Digital Sky Survey (SDSS), 9–10, 141
Sloan Great Wall, 271
Small Magellanic Cloud, 202, 224, 226
Smoot, George, 272
SN 1006, 184
SN 1987A. *See* Supernova 1987A
SnIa. *See* Type Ia supernova (SnIa)
SNO. *See* Sudbury Neutrino Observatory (SNO)
SOFIA. *See* Stratospheric Observatory for Infrared Astronomy (SOFIA)
Sojourner, 330
Solar activity, 110–117
Solar day, 37
Solar eclipse, 17, 32–33
Solar eruptions, 115
Solar flares, 117
Solar magnetic cycle, 111, 114
Solar nebula theory, 278–279, 290, 292, 294–295
Solar neutrino problem, 153
Solar system, 276–303
  age, 287–288
  asteroids, 280–281

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bombardment of the planets, 292–293
catastrophic theory, 294
characteristic properties, 288
chemical composition of solar nebula, 289
comets, 281, 284–285
condensation of solids, 289–290
condensation sequence, 289
debris disks, 296
defined, 7
dwarf planets, 351–354
evolutionary system, 294
heat of formation, 295
Jovian planets. *See* Jovian planets
Kuiper belt, 284
meteoroids, meteors, meteorites, 285–287
planetesimals, 290
principal satellites, 383
protoplanets, 290–292
revolution and rotation, 306
scale, 306
solar nebula theory, 278–279, 290, 292, 294–295
space debris, 280–287
terrestrial planets. *See* Terrestrial planets
unmanned spacecraft studying asteroids/comets, 285
Solar wind, 110
Solar year, 37
Somayaji, Nilakantha, 51
Sound waves, 74
South celestial pole, 22
South point, 22
Space aliens, 371
Space debris, 280–287
Spaceguard programs, 293
Space-time
curvature of, 272–273
theory of, 188–189
Spaghettification, 194
Special theory of relativity, 188–189
Spectral class, 126
Spectral line, 94
Spectral sequence, 127
Spectral types, 126
Spectrograph, 85–86
Spectroscopic binary system, 134–135
Spectroscopic parallax, 132
Spectrum, 85
Speed, 62
Speed of light, 74
Spherical component, 206
Spica, 40
Spicule, 108
Spiral arms, 10, 206, 209–212
Spiral density wave theory, 211
Spiral galaxy, 206, 210–211, 227, 230, 241
Spiral tracer, 209–210
Spirit rover, 326
SPIRou, 297
Spitzer Space Telescope, 88, 231
Splash crater, 325
Spring tides, 68
Square Kilometre Array (SKA), 83
SS 433, 193
Standard candle, 229–230
Standard Model, 153, 259
Star. *See* Stars
Star charts, 384–386
Star classification system, 126–127
Star cluster, 162, 173
Star cluster H–R diagrams, 174–175
Star formation, 156–166, 209–212
Star trails, 22
Starburst galaxy, 239
Stardust, 285
Stars, 120–167
absolute visual magnitude, 124–125
binary, 132–134
birth/formation, 156–166, 209–212
brightest, 139, 381
brightness, 19–21, 124
brown dwarf, 127, 154–155
constellations, 18–19
death. *See* Death of stars
defined, 7
density, 137
diameter (size), 129–132
diffraction fringes, 78
distance between, 370
distance from Earth, 122–123
four laws of stellar structure, 146–148
giant, 131, 171
H–R diagram, 129–131, 172
L dwarf, 127
life expectancy, 155–156
luminosity, 124–125, 129–132
luminosity class, 132
main sequence. *See* Main-sequence stars
mass, 132–134
mass–luminosity relation, 137
names, 19
nearest, 139, 380
neutron, 185–188
night sky tours, 38–42
nuclear fusion, 150–154
parsec, 123
proper motion, 203
red dwarf, 131
Roche lobe, 178
size, 129–132
spectral class, 126
spectroscopic parallax, 132
stellar model, 146–149
stellar parallax, 122
supergiant, 131
surveying the stars, 140–141
T dwarf, 127–128
temperature, 125–128
twinkling, 79
visualizing astronomy, 138–139
wandering, 4
white dwarf, 131–132

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Statistical evidence, 245
Stefan–Boltzmann law, 96, 131
Stellar association, 162
Stellar coordinates, 36
Stellar habitable zone, 369
Stellar mass, 132–134
Stellar model, 146–149
Stellar parallax method, 228
Stellar parallax *(p),* 122
Stellar populations, 212–213
Stellar spectra, 128
Stonehenge, 47
Stony meteorite, 286
Stony-iron meteorite, 286
Stratospheric Observatory for Infrared Astronomy (SOFIA), 86
Stromatolite, 359
Styx, 354
Subduction zone, 310
Subgiant, 132
Sudbury Neutrino Observatory (SNO), 153–154
Summer solstice, 28
Summer solstice light, 29
Sun, 92–119
  annual motion, 25
  celestial profile, 391
  chemical composition, 103, 106
  chromosphere, 106–108
  chromospheric and coronal activity, 114–115
  convective zone, 147, 149
  corona, 108–109
  cycle of, 25–27
  death, 177–178
  distance and size, 7, 94–95
  filament, 108
  G2 star, 127
  granulation, 98–99
  habitable zone, 369
  heat flow, 98
  helioseismology, 111
  loss of mass, 109
  luminosity, 125
  magnetic carpet, 109
  magnetic cycle, 111, 114
  magnetic solar phenomena, 116–117
  main-sequence star, 154–156
  mass and density, 95
  neutrinos, 152–153
  nuclear fusion, 150–154
  observing the Sun, 110
  photosphere, 97–98
  radiative zone, 147, 149
  rotation of, 279
  size, 7
  solar eruptions, 115
  solar wind, 109
  spectra, 103
  spicule, 108
  stellar model, 148–149
  sunspots, 98, 110–113
Sunlike stars, 170
Sunspot, 98, 110–113
Sunspot cycle, 111–113
Sunspot groups, 114
Supercluster, 10
Supergiant star, 131, 137, 171
Super-Kamiokande experiment, 153
Supermassive black hole, 219, 241, 247. *See also* Black hole
Supernova, 170
Supernova 1006, 184
Supernova 1987A, 183–185
Supernova Cosmology Project, 6
Supernova explosion, 161, 181–182, 230
Supernova explosion (1054 ce), 47–48, 182
Supernova remnant, 184–185
Surveyor's triangulation method, 122
Swan (Cygnus), 42
Synodic month, 37
Synodic period, 31
Système International d'Unités (SI units), 378

T

T dwarf, 127–128
T Tauri star, 163
Tagish Lake meteorite, 288
Tarantula Nebula, 157
Tarter, Jill, 169
Taurus, 38
Taurus the Bull, 182
Teapot, 19
Technological civilizations, 373
Telescope. *See* Astronomical telescopes
Temperature, 96
Temperature scales, 378
Temperature spectral classification, 126–127
Templo Mayor, 47
Tereshkova, Valentina, 305
Terrestrial planets, 280, 282–283, 304–333
  Earth. *See* Earth
  Mars. *See* Mars
  Mercury, 318–319
  Venus, 319–322, 328
  visualizing astronomy, 282–283
Tethys, 383
Thales of Miletus, 49
Tharsis region (Mars), 323
Theory, 60
Thermal energy, 96
Third-quarter moon, 31
Thomson, William (Lord Kelvin), 378
Tidal heating, 342
Tidal tail, 238
Tides, 65, 68
Time (cosmic calendar), 12–13
Time dilation, 189
Timekeeping
  apparent solar time, 37
  calendars, 37–38
  sidereal day, 37
  sidereal month, 37

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sidereal year, 37
solar day, 37
solar year, 37
synodic month, 37
tropical year, 37
Timeline, 46, 50, 54
Titan, 332, 345, 383
Titania, 383
Titanium oxide, 128
Tlingit, 166
TNOs. *See* Trans-Neptunian objects (TNOs)
Top-down galaxy formation, 214
Total eclipse, 32, 34
Transit method, 298–299
Transiting Exoplanet Survey Satellite (TESS), 87, 297
Transition, 105
Transits of Venus, 94–95
Trans-Neptunian objects (TNOs), 354
Trapezium, 164–165
TRAPPIST-1 system, 300–301, 369–370
Triton, 350, 383
Tropical year, 37
Tully-Fisher relationship, 230
Turnoff point, 174
Twinkling of a star, 79
Twins (Gemini), 39
Two Micron All Sky Survey (2MASS), 141, 232
Tycho's supernova, 183
Type I supernova, 180, 182
Type Ia supernova (SnIa), 230
Type Ib supernova, 182
Type II supernova, 182

U

UCLA Milky Way Center Group, 219
UFOs. *See* Unidentified flying objects (UFOs)
Ultraviolet (UV), 76
Umbra, 32
Umbriel, 383
Uncompressed density, 289
Unidentified flying objects (UFOs), 371
Unified model, 247
Uniform circular motion, 52
Units and astronomical data
astronomical constants, 379
astronomy units, 379
brightest stars, 381
main-sequence stars, 379
metric system, 378
nearest stars, 380
planets, properties, 382
SI units, 378
solar system, principal satellites, 383
temperature scales, 378
Universal mutual gravitation, 64
Universal theory of gravitation, 63–64
Universe. *See* Cosmology
Universe of Particles, 6, 8
Upper-main-sequence stars, 152
Uranus, 279, 348–351, 383, 390
Urban VIII (Pope), 62
Urey, Harold, 362
Ursa Major, 19, 40
Ursa Minor, 40

V

V404 Cygni, 194
Valles Marineris, 324, 330
Valley network, 325
Van Gogh, Vincent, 121
Vanth, 354
Velocity, 62
Venera 13 lander, 321
Venus, 279, 307
atmosphere, 320
celestial profile, 387
history, 321–322
runaway greenhouse, 328
size, 7
surface, 320–321
Venus Express, 322
Vernal equinox, 28
Very Large Telescope (VLT), 80–81
Very Long Baseline Interferometry (VLBI), 84
Vesta (asteroid), 281
Via lactea, 200
Viking 1, 368
Viking 2, 368
Viking orbiters, 325
Violet, 75
Virgo cluster, 253
Virgo (the Virgin), 40
Visible and Infrared Survey Telescope for Astronomy (VISTA), 86
Visible light, 75
Visual binary system, 134
Visual spectrum, 86–87
Visualizing astronomy
ancient universe, 52–53
astronomical telescopes, 82
atomic spectra, 104–105
DNA, 360–361
Earth, 310–311
galaxy classification, 226–227
Jupiter, 340–341
Large Hadron Collider (LHC), 258–259
magnetic solar phenomena, 116–117
Mars, 329
Moon phases, 30–31
nebulae, 158–159
orbiting Earth, 66–67
power of 10, 8–9
Sagittarius A*, 216–217
Saturn, 346–347
seasons, 28–29
sky around us, 22–23
star cluster H–R diagrams, 174–175
star formation (Orion Nebula), 164–165
stars, 138–139

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Visualizing astronomy (*continued*)
sunspots and sunspot cycle, 112–113
terrestrial and Jovian planets, 282–283
Venus, 328
Vitamin D, 118
VLBI. *See* Very Long Baseline Interferometry (VLBI)
VLT. *See* Very Large Telescope (VLT)
Volatile, 284
Volcano, 323
von Braun, Wernher, 317
Voyager 1 spacecraft, 345
Voyager 2 spacecraft, 345, 348–350

W

Walker, G. A. H., 299
Wandering stars, 4
Wang Yaping, 93
Waning crescent, 30
Waning gibbous, 30
Water hole, 371
Wavelength
definition of, 74
of maximum intensity, 96
ranges of, 76
Waxing crescent, 30
Waxing gibbous, 30
Wayfinding, 49
Weakly interacting massive particles (WIMPs), 209
Weight, 64
West point, 22
Weywot, 354
White dwarf, 131–132, 138, 176–177
White-hot, 95
Wien's law, 96, 98
Wilkinson, David, 256
Wilkinson Microwave Anisotropy Probe (WMAP), 272
Wilson, Robert, 254–255
WIMPs. *See* Weakly interacting massive particles (WIMPs)
Windmills, 118
Winged Horse (Pegasus), 42
Winter solstice, 28
Winter solstice light, 29
WMAP. *See* Wilkinson Microwave Anisotropy Probe (WMAP)

X

X-ray binaries, 192
X-rays, 76, 192

Y

Y dwarf, 128
Yang, S., 299
Yellow-hot, 95

Z

Zeeman effect, 111, 113
Zenith, 22
Zero-age main sequence (ZAMS), 155
Ziliang Jin, 5
Zircons, 309
Zwicky, Fritz, 185, 234

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The Scale of the Cosmos: Space and Time

TOPIC SUMMARIES

1.1 Astronomy: A Global Human Adventure

How are humans working together to answer big questions of existence and place in the universe?

- The study of astronomy incorporates concepts from both physical and biological sciences. The story of astronomy is a story of collective human knowledge.
- International coalitions of scientists and engineers build grand telescopes, collect observations, and share the results in public databases.
- Spacecraft from different countries explore bodies of the solar system and the origin and composition of planets, moons, asteroids and, comets.

1.2 From Solar System to Galaxy to Universe

Where is Earth in relation to the Sun, the planets, the stars, and the galaxies?

- We live on planet Earth, which orbits our star, the Sun, once a year.
- As Earth rotates once a day, we see the Sun rise and set.
- The other major planets in our solar system—Mercury, Venus, Mars, Jupiter, Saturn, Uranus, and Neptune—orbit our Sun in ellipses that are nearly circular.
- Our Sun is just one out of the billions of stars that fill our home galaxy, the Milky Way, which is a spiral galaxy.
- The Milky Way Galaxy is just one of billions of galaxies arranged in great clusters, clouds, walls, and filaments that fill the universe.

How do astronomers describe distances?

- Astronomers use scientific notation for very large or very small numbers.
- Astronomers have also invented new units of measure such as the astronomical unit (AU) and the light-year (ly). One AU is the average distance from Earth to the Sun. Mars, for example, orbits 1.5 AU from the Sun. The light-year is the distance light can travel in one year. The nearest star is 4.2 ly from the Sun.

Which of these objects are big relative to the others, and which are small?

- The Moon is only about one-fourth the diameter of Earth, but the Sun is about 110 times larger than Earth—a typical size for a star.
- Galaxies contain many billions of stars. We live in the Milky Way Galaxy, which is about 80 000 ly in diameter and contains over 100 billion stars.
- The largest things in the universe are the walls and long filaments containing many clusters of galaxies.

Are there other worlds like Earth?

- Planets as small as Earth are difficult to detect around other stars. Many stars have families of planets like our solar system, and some of those billions of planets may resemble Earth.

1.3 The Cosmic Calendar: Concepts of Time

Suppose you constructed a cosmic calendar spread over an average human lifetime (80 years) instead of over a calendar year. How would the timing of some of the important features of the universe's development change?

- The Milky Way gets created during your teen years.
- Our solar system is formed as you turn 50 years old.
- The dinosaurs roam Earth when you are about 79 years old.
- All of recorded history occurs in the last 6.6 seconds of your life.

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Which time frames are relatively large, and which are small?

- The oldest known entity is, in fact, the universe. Whether time even existed before the big bang is mere speculation.
- The Sun's age is about 5 billion years. It is assumed that it will last about another 5 billion years or so, at which time it will become a white dwarf, cooling down over millions of years and eventually becoming a black cinder of mostly carbon. It will stay in this form until the universe dies.
- The average sparrow lives for about three years.
- The half-life of the isotope beryllium-8 (^{8}Be) is about 70×10^{-18} seconds.

KEY TERMS

scientific notation The system of recording very large or very small numbers by using powers of 10. (p. 6)

field of view The area visible in an image, usually given as the diameter of the region. (p. 6)

astronomical unit (AU) Average distance from Earth to the Sun; 1.5×10^{8} kilometres. (p. 7)

solar system The Sun and its planets, asteroids, comets, and so on. (p. 7)

planet A nonluminous body in orbit around a star, large enough to be spherical and to have cleared its orbital zone of other objects. (p. 7)

star A globe of gas held together by its own gravity and supported by the internal pressure of its hot gases, which generates energy by nuclear fusion. (p. 7)

light-year (ly) Unit of distance equal to the distance light travels in one year. (p. 10)

galaxy A large system of stars, star clusters, gas, dust, and nebulae orbiting a common centre of mass. (p. 10)

Milky Way The hazy band of light that circles our sky, produced by the glow of our galaxy. (p. 10)

Milky Way Galaxy The spiral galaxy containing our Sun, visible in the night sky as the Milky Way. (p. 10)

spiral arms Long spiral pattern of bright stars, star clusters, gas, and dust. Spiral arms extend from the centre to the edge of the disk of spiral galaxies. (p. 10)

supercluster A cluster of galaxy clusters. (p. 10)

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User's Guide to the Sky: Patterns and Cycles

TOPIC SUMMARIES

2.1 The Stars

How do astronomers refer to stars?

- Astronomers divide the sky into 88 constellations with names that originated in Greek and Middle Eastern mythology. Modern constellations have been added to fill in spaces.
- Modern astronomers often refer to bright stars by a name composed of the constellation name plus a Greek letter assigned according to the star's brightness within the constellation.

How can you compare the brightness of stars?

- The magnitude system is the astronomer's brightness scale. First-magnitude stars are brighter than second-magnitude stars, which are brighter than third-magnitude stars, and so on.
- The magnitude you see when you look at a star in the sky is its apparent visual magnitude, which does not take into account its distance from Earth.

2.2 The Sky and Its Motions

How does the sky appear to move as Earth rotates?

- The celestial sphere is a model of the sky. The northern and southern celestial poles are the pivots on which the sky appears to rotate. The celestial equator, an imaginary line around the sky above Earth's equator, divides the sky in half.
- The angular distance from the horizon to the north celestial pole always equals your latitude. This is an important basis for celestial navigation.
- The gravitational forces of the Moon and Sun act on the spinning Earth and cause it to precess like a top. Earth's axis of rotation sweeps around in a circular motion with a period of 26 000 years, and consequently the celestial poles and celestial equator move slowly against the background of the stars.

2.3 The Cycle of the Sun

What causes the seasons?

- Because Earth orbits the Sun, the Sun appears to move eastward along the ecliptic. The inclination of the ecliptic means the Sun is in the northern hemisphere half the year and in the southern hemisphere the other half.
- In the summer, the Sun is above the horizon longer and shines more directly down on the ground. Both effects cause warmer weather.

2.4 The Cycles of the Moon

Why does the Moon go through phases?

- Because you see the Moon by reflected sunlight, its shape appears to change as it orbits Earth over a cycle of 29.53 days.

2.5 Eclipses

What is a solar eclipse?

- A total solar eclipse occurs if a new Moon passes directly between the Sun and Earth and the Moon's shadow sweeps over the part of Earth's surface where you are located. If you are outside the path of totality but the penumbra sweeps over your location, you see a partial eclipse.
- During a total solar eclipse, the bright disk of the Sun is covered, and you can see fainter features of the surrounding solar atmosphere.
- If the Moon is in the farther part of its orbit during a solar eclipse, it does not appear large enough to cover the solar disk, and you see only an annular eclipse.

What is a lunar eclipse?

- If a full Moon passes through Earth's shadow while you are on the night side of Earth, you see the Moon darken in a lunar eclipse.
- The totally eclipsed Moon looks copper-red because of sunlight refracted through Earth's atmosphere.

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2.6 Stellar Coordinates

How do we locate the position of a star in the sky?

- The celestial sphere uses a coordinate grid similar to the longitude and latitude system used on Earth. Declination on the celestial sphere is identical to latitude, while right ascension is similar to longitude, with the zero of right ascension (RA) being the location of the vernal equinox on the celestial sphere.

2.7 Timekeeping

How do we determine the length of a day on Earth?

- There are two ways to measure the length of a day on Earth: one uses the time for successive crossings of the Sun on the meridian, called a solar day; the other uses the time for successive crossings of any particular star on the meridian, called a sidereal day. A sidereal day is shorter than a solar day by about four seconds.

KEY TERMS

constellation One of the stellar patterns identified by name, usually of mythological gods, people, animals, or objects; also the region of the sky containing that star pattern. (p. 18)

asterism A named grouping of stars that is not one of the recognized constellations. (p. 19)

magnitude scale The astronomical brightness scale; the larger the number, the fainter the star. (p. 19)

apparent visual magnitude (m_v) A measure of the brightness of a star as seen by human eyes on Earth. (p. 20)

flux A measure of the flow of energy per time through a surface, usually applied to light. (p. 20)

celestial sphere An imaginary sphere of very large radius surrounding Earth to which the planets, stars, Sun, and Moon seem to be attached. (p. 21)

scientific model A concept that helps one think about some aspect of nature, but is not necessarily true. (p. 21)

zenith The point in the sky directly above the observer. (p. 22)

nadir The point on the celestial sphere directly below the observer; the opposite of the zenith. (p. 22)

north, south, east, and west points The four cardinal directions; the points on the horizon in those exact directions. (p. 22)

precession The slow change in orientation of Earth's axis of rotation. One cycle takes nearly 26 000 years. (p. 24)

rotation Motion around an axis passing through the rotating body. (p. 25)

revolution Orbital motion about a point located outside the orbiting body. (p. 25)

ecliptic The apparent path of the Sun around the sky. (p. 25)

vernal equinox The place on the celestial sphere where the Sun crosses the celestial equator moving northward; also the beginning of spring. (p. 28)

summer solstice The point on the celestial sphere where the Sun is at its most northerly point; also the beginning of summer. (p. 28)

autumnal equinox The point on the celestial sphere where the Sun crosses the celestial equator going southward; also the beginning of autumn. (p. 28)

winter solstice The point on the celestial sphere where the Sun is farthest south; also the beginning of winter. (p. 28)

perihelion The orbital point of closest approach to the Sun. (p. 29)

aphelion The orbital point of greatest distance from the Sun. (p. 29)

solar eclipse The event that occurs when the Moon passes directly between Earth and the Sun, blocking our view of the Sun. (p. 32)

umbra The region of a shadow that is totally shaded. (p. 32)

penumbra The portion of a shadow that is only partially shaded. (p. 32)

annular eclipse A solar eclipse in which the solar photosphere appears around the edge of the Moon in a bright ring, or annulus. Features of the solar atmosphere cannot be seen during an annular eclipse. (p. 33)

lunar eclipse The darkening of the Moon when it moves through Earth's shadow. (p. 33)

Saros cycle An 18-year, $11^1/_3$-day period, after which the pattern of lunar and solar eclipses repeats. (p. 35)

declination The angular distance of an object on the celestial sphere measured north (+) or south (−) from the celestial equator. (p. 36)

right ascension The angular east-west distance of an object on the celestial sphere measured from the vernal equinox; measured in hours, minutes, and seconds rather than angular degrees. (p. 36)

celestial equator The imaginary line around the sky directly above Earth's equator. (p. 36)

solar day The average time between successive crossings of the Sun on the local meridian (24 hours). (p. 37)

sidereal day The time between successive crossings of any star on the local meridian (23 hours, 56 minutes, 4.09 seconds). (p. 37)

synodic month The time for a complete cycle of lunar phases (about 29.5 days). (p. 37)

sidereal month The time for the Moon to orbit Earth once relative to any star (about 27.3 days). (p. 37)

sidereal year The time for Earth to complete one full orbit around the Sun relative to any star. (p. 37)

tropical year (solar year) The time between successive spring (or autumnal) equinoxes. (p. 37)

apparent solar time Time measured by the location of the Sun in the local sky such that noon occurs when the Sun crosses the meridian. (p. 37)

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The Origin of Modern Astronomy

TOPIC SUMMARIES

3.1 The Birth of Astronomy

What did ancient civilizations achieve in astronomy?

- Ancient astronomers all over the world observed the sky and recognized patterns in the motion of the Sun, Moon, planets, and bright stars.
- The motions of celestial bodies were used for daily and monthly timekeeping, tracking seasons for agricultural purposes, and navigation. Many ceremonies and festivals grew around monthly and seasonal changes.
- The Greeks were among the first to develop models to explain what they observed in the universe.

What was the geocentric model?

- Ancient philosophers believed that Earth was the unmoving centre of the universe.
- Aristotle argued that the Sun, Moon, and stars were carried around Earth on circular spheres.
- Ptolemy gave mathematical form to Aristotle's model in about 140 CE. He kept the geocentric (Earth-centred) principle, but he added off-centre circles and variable speeds to better predict the motion of the planets. Later Arab astronomers preserved and corrected his model.

3.2 A Revolutionary Idea

How was the geocentric model revised?

- Copernicus built on ideas proposed by Greek, Indian, and Arab astronomers to devise a heliocentric (sun-centred) model. He mistakenly preserved the principle of uniform circular motion, but he argued that Earth rotates on its axis and circles the Sun once a year.
- The Copernican theory was controversial because it contradicted church teaching. Copernicus published his theory in his book *De Revolutionibus* in 1543, the year he died.
- Because Copernicus kept the idea of uniform circular motion, his model did not predict the motions of the planets well, but it did offer a simple explanation of retrograde motion of planets without using large epicycles (circles on circles). He did have to include small epicycles to account for some observed planetary motions.
- The Copernican model was also more eloquent and straightforward. Venus and Mercury were treated the same as all the other planets, and the velocity of each planet was related to its distance from the Sun.

3.3 Observing the Patterns of Planetary Motion

What patterns were discovered in the motion of the planets?

- Tycho's great contribution was to compile precise and detailed naked-eye observations of the planets and stars; his observations were later analyzed by Kepler.
- Kepler inherited Tycho's books of observations in 1601 and used them to uncover three laws of planetary motion. He found that the planets follow ellipses with the Sun at one focus, that they move faster when near the Sun, and that a planet's orbital period squared (in years) is proportional to its orbital radius cubed (in AU).

3.4 A New Window on the Universe

What observations helped to support the heliocentric model?

- Galileo used the newly invented telescope to observe the heavens, and he recognized the significance of what he saw there. His discoveries of the phases of Venus, the satellites of Jupiter, the mountains of the Moon, and other phenomena helped undermine the geocentric model.
- Galileo based his analysis on observational evidence. In 1633, he was condemned before the Inquisition for refusing to obey an order to halt his defence of the heliocentric model.

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3.5 The Science of Motion

What are the laws of motion and gravity?

- Newton used the work of Kepler and Galileo to discover three laws of motion and the law of gravity. These laws made it possible to understand such phenomena as orbital motion and the tides.
- Newton's laws gave scientists a unified way to think about the motion of all objects in the universe.
- The modern scientific method based on gathering evidence, creating models, and testing theories owes its origins to the efforts of Newton and his predecessors all the way back to our ancient ancestors.

KEY TERMS

first principle Something that seems obviously true and needs no further examination. (p. 50)

uniform circular motion The classical belief that the perfect heavens could move only by the combination of uniform motion along circular orbits. (p. 52)

parallax The apparent change in position of an object due to a change in the location of the observer. Astronomical parallax is measured in arc seconds. (p. 52)

retrograde motion The apparent backward (westward) motion of planets as seen against the background of stars. (p. 52)

epicycle The small circle followed by a planet in the Ptolemaic theory. The centre of the epicycle follows a larger circle (the deferent) around Earth. (p. 53)

geocentric universe A model of the universe with Earth at the centre, such as the Ptolemaic universe. (p. 54)

heliocentric universe A model of the universe with the Sun at the centre, such as the Copernican universe. (p. 54)

paradigm A commonly accepted set of scientific ideas and assumptions. (p. 57)

ellipse A closed curve around two points, called foci, such that the total distance from one focus to the curve and back to the other focus remains constant. (p. 57)

semi-major axis (*a*) Half of the longest diameter of an ellipse. (p. 58)

eccentricity (e) A number between 1 and 0 that describes the shape of an ellipse (how elongated it is); the distance from one focus to the centre of the ellipse, divided by the semi-major axis. (p. 58)

empirical Description of a phenomenon based only on observations and without explaining why it occurs. (p. 59)

hypothesis A conjecture, subject to further tests, that accounts for a set of facts. (p. 60)

theory A system of assumptions and principles applicable to a wide range of phenomena that has been repeatedly verified. (p. 60)

natural law A theory that has been so well confirmed that it is almost universally accepted as correct. (p. 60)

speed The rate at which an object moves (changes position); the total distance moved divided by the total time taken to move that distance. (p. 62)

velocity Both the speed and direction of travel of an object. (p. 62)

acceleration The rate of change of velocity with time. (p. 63)

mass A measure of the amount of matter making up an object. (p. 64)

weight The force that gravity exerts on an object. (p. 64)

inverse square relation A rule that the strength of an effect (such as gravity) decreases in proportion as the distance squared increases. (p. 64)

circular velocity The velocity an object needs to stay in orbit around another object. (p. 66)

geosynchronous satellite A satellite that orbits eastward around Earth with a period of 24 hours and remains above the same spot on Earth's surface. (p. 66)

centre of mass The balance point of a body or system of masses. The point about which a body or system of masses rotates in the absence of external forces. (p. 67)

closed orbit An orbit that repeatedly returns to the same starting point. (p. 67)

escape velocity The initial velocity an object needs to escape from the surface of a celestial body. (p. 67)

open orbit An orbit that carries an object away, never to return to its starting point. (p. 67)

spring tide Ocean tide of large range that occurs at full and new moon. (p. 68)

neap tide Ocean tide of small range occurring at first- and third-quarter moon. (p. 68)

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Astronomical Telescopes and Instruments: Extending Humanity's Vision

TOPIC SUMMARIES

4.1 Radiation: Information from Space

What is light?

- Light is the visible form of electromagnetic radiation. The electromagnetic spectrum includes gamma rays, X-rays, ultraviolet radiation, visible light, infrared radiation, microwaves, and radio waves.
- You can think of a photon as a bundle of waves that acts sometimes as a particle and sometimes as a wave.
- The wavelength of visible light, usually measured in nanometres (10^{-9} m), ranges from 400 nm to 700 nm. Infrared and radio photons have longer wavelengths and carry less energy. Ultraviolet, X-ray, and gamma-ray photons have shorter wavelengths and carry more energy.

4.2 Telescopes

How do telescopes work? What are their capabilities and limitations?

- Astronomers use telescopes to gather light, see fine detail, and magnify images. Two of the three powers of a telescope—light-gathering power and resolving power—depend on the telescope's diameter. Consequently, astronomers strive to build telescopes with large diameters.
- Sometimes astronomical telescopes can be linked together to form an interferometer, which has a resolution equivalent to a telescope as large in diameter as the greatest separation between the individual telescopes.
- The third power of a telescope—magnifying power—is not an inherent property of a telescope but depends on which eyepiece is used.

4.3 Observatories on Earth: Optical and Radio

How are observatories built, and how are good locations chosen for them?

- Astronomers build optical observatories on high mountains for two reasons: the seeing is better in the calmer and dryer air, and the thinner air is more transparent, especially at infrared wavelengths.
- Radio telescopes consist of one or more large-dish reflectors, which record the intensity of the radio energy coming from a spot in the sky.
- Optical and radio telescopes need to be located where light pollution and human-made radio signals do not interfere with observations of faint cosmic sources.
- Telescopes on Earth must move continuously to compensate for Earth's rotation and stay pointed at celestial objects.

4.4 Astronomical Instruments and Techniques

What kinds of instruments and techniques do astronomers use to record and analyze light?

- For many decades, astronomers used photographic plates and photometers, but modern electronic array detectors such as charge-coupled devices (CCDs) have replaced them in most applications.
- Spectrographs using prisms or a grating can form a spectrum revealing information about the composition and motion of the object being studied.

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4.5 Airborne and Space Observatories

Why do astronomers sometimes use X-ray, ultraviolet, and infrared telescopes, and why must these types of telescopes operate in the upper atmosphere or in orbit?

- X-ray, UV, and IR telescopes observe radiation from celestial objects at a wide range of temperatures and can also see through obscuring dust clouds in space.
- To observe wavelengths outside the visual window and the radio window permitted by our atmosphere, telescopes must go into the upper atmosphere or into space.
- Earth's atmosphere distorts and blurs images. Telescopes in orbit are above this seeing distortion and are limited only by diffraction fringes.

KEY TERMS

electromagnetic radiation Changing electric and magnetic fields that travel through space and transfer energy from one place to another; examples are light or radio waves. (p. 74)

wavelength The distance between successive peaks or troughs of a wave, usually represented by a lowercase Greek lambda, λ. (p. 74)

infrared (IR) The portion of the electromagnetic spectrum with wavelengths longer than red light, ranging from 700 nm to about 1 mm, between visible light and radio waves. (p. 75)

ultraviolet (UV) The portion of the electromagnetic spectrum with wavelengths shorter than violet light, between visible light and X-rays. (p. 76)

X-rays Electromagnetic waves with wavelengths shorter than ultraviolet light. (p. 76)

gamma rays The shortest-wavelength electromagnetic waves. (p. 76)

photon A quantum of electromagnetic energy that carries an amount of energy that increases proportionally with its frequency, but decreases proportionally with its wavelength. (p. 76)

atmospheric window Wavelength region in which our atmosphere is transparent—at visual, radio, and some infrared wavelengths. (p. 76)

refracting telescope A telescope that forms images by bending (refracting) light with a lens. (p. 77)

reflecting telescope A telescope that forms images by reflecting light with a mirror. (p. 77)

primary lens In a refracting telescope, the largest lens. (p. 77)

primary mirror In a reflecting telescope, the largest mirror. (p. 77)

eyepiece A short-focal-length lens used to enlarge the image in a telescope; the lens nearest the eye. (p. 77)

focal length The focal length of a lens or mirror is the distance from that lens or mirror to the point where it focuses parallel rays of light. (p. 77)

optical telescope Telescope that gathers visible light. (p. 77)

radio telescope Telescope that gathers radio radiation. (p. 77)

light-gathering power The ability of a telescope to collect light; proportional to the area of the telescope's objective lens or mirror. (p. 78)

resolving power The ability of a telescope to reveal fine detail; depends on the diameter of the telescope objective. (p. 78)

diffraction fringe Blurred fringe surrounding any image, caused by the wave properties of light. Because of this, no image detail smaller than the fringe can be seen. (p. 78)

interferometer Separated telescopes combined to produce a virtual telescope with the resolution of a much larger-diameter telescope. (p. 78)

seeing Atmospheric conditions on a given night. When the atmosphere is unsteady, producing blurred images, the seeing is said to be poor. (p. 79)

adaptive optics A computer-controlled optical system in an astronomical telescope used to partially correct for seeing. (p. 80)

magnifying power The ability of a telescope to make an image larger. (p. 80)

sidereal tracking The continuous movement of a telescope to keep it pointed at a star as Earth rotates. (p. 81)

prime focus The point at which the objective mirror forms an image in a reflecting telescope. (p. 82)

secondary mirror In a reflecting telescope, a mirror that directs the light from the primary mirror to a focal position. (p. 82)

Cassegrain focus The optical design in which the secondary mirror reflects light back down the tube through a hole in the centre of the objective mirror. (p. 82)

photometer Sensitive astronomical instrument that measures the brightness of individual objects very precisely. (p. 84)

charge-coupled device (CCD) An electronic device consisting of a large array of light-sensitive elements used to record very faint images. (p. 84)

spectrograph A device that separates light by wavelengths to produce a spectrum. (p. 85)

spectrum A range of electromagnetic radiation spread into its component wavelengths (colours)—for example, a rainbow; also the representation of a spectrum as a graph showing intensity of radiation as a function of wavelength or frequency. (p. 85)

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The Sun: The Closest Star

TOPIC SUMMARIES

5.1 The Sun: Basic Characteristics

How do you know the distance, size, mass, and density of the Sun?

- Observing the parallax shift of Venus in transit against the Sun's disk from opposite sides of Earth was the original method for finding the distance to the Sun. The diameter of the Sun can be calculated from its distance and its angular size.
- Newton's laws and the motion of the planets as they orbit the Sun allow the mass of the Sun to be determined. Its average density can be easily calculated from its mass and diameter.

5.2 Properties of Blackbody Radiation

How does matter produce light?

- Motion among charged particles in a solid, a liquid, or a dense gas causes the emission of blackbody radiation. Pure blackbody radiation is a continuous spectrum.
- The hotter an object is, the more energy it radiates and the shorter is its wavelength of maximum intensity, λ_{max}. This allows astronomers to estimate the temperature of the Sun and other stars from their colours.

5.3 The Sun's Surface

What do astronomers see when they observe the Sun?

- The photosphere is the level in the Sun from which visible photons most easily escape. Its temperature is about 5800 K.
- Energy flowing outward from the Sun's interior travels as rising currents of hot gas and sinking currents of cool gas in the convective zone just below the photosphere.
- The granulation of the photosphere is produced by convection currents of gas rising from below.

5.4 Light, Matter, and Motion

How does matter interact with light to produce spectral lines?

- Electrons in an atom may occupy various permitted orbits around the nucleus but not orbits in between. The size of an electron's orbit depends on the energy stored in the electron's motion.
- An electron may be excited to a higher orbit during a collision between atoms, or it may move from one orbit to another by absorbing or emitting a photon of the proper energy.
- A shift in the wavelength of features in spectra of the Sun and stars can occur due to their motion toward or away from Earth. This phenomenon, called the Doppler effect, reveals the radial velocity of the star, the part of its velocity directed toward Earth (blueshift) or away from Earth (redshift).

5.5 The Sun's Atmosphere

What can you learn from the Sun's spectrum?

- Because orbits of only certain energies are permitted in an atom, photons of only certain wavelengths can be absorbed or emitted. Each kind of atom has its own structure and therefore its own characteristic set of spectral lines.
- If light from a blackbody such as the Sun's photosphere passes through a low-density gas such as the Sun's atmosphere on its way to your spectrograph, the gas can absorb photons of certain wavelengths, producing an absorption spectrum.
- The Sun's spectrum can tell you its chemical composition through the presence of spectral lines of a certain element. However, you must proceed with care because the strengths of lines also depend on the temperature of the gas.

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- If you look at a low-density gas that is excited to emit photons, you see an emission spectrum.
- The solar atmosphere consists of two layers of hot, low-density gas: the chromosphere and the corona.
- The chromosphere is most easily visible during total solar eclipses. Its pink colour is caused by the Balmer emission lines in its spectrum. Filtergrams of the chromosphere reveal spicules and filaments.
- The corona is the Sun's outermost atmospheric layer. It is composed of a very-low-density, very hot gas extending far from the visible Sun. Astronomers have evidence that its high temperature—2000000 K or more—is maintained by effects of the magnetic carpet.
- Parts of the corona give rise to the solar wind.

5.6 Solar Activity

What is the solar cycle of activity, and how does that affect Earth?

- Sunspots seem dark because they are slightly cooler than the rest of the photosphere. The average sunspot is about twice the size of Earth and contains magnetic fields a few thousand times stronger than Earth's.
- Solar astronomers can study the motion, density, and temperature of gases inside the Sun through helioseismology.
- Astronomers can measure magnetic fields on the Sun by measuring the splitting of some spectral lines caused by the Zeeman effect.
- The average number of sunspots varies over a period of about 11 years and appears to be related to a magnetic cycle.
- The Sun rotates differentially, with regions far from the equator rotating slower than equatorial regions.
- Spectroscopic observations of other stars reveal that many have spots and magnetic fields that follow long-term cycles like the Sun's.
- Prominences occur in the chromosphere; their arched shapes show that they are formed of ionized gas trapped in the magnetic field.
- Flares are sudden eruptions of X-ray, ultraviolet, and visible radiation plus high-energy atomic particles produced when magnetic fields on the Sun interact and reconnect. Flares are important because they can have dramatic effects on Earth, such as communications blackouts and auroras.
- Spacecraft images show long streamers extending from the corona out into space. CMEs can produce auroras and other phenomena if they strike Earth.

KEY TERMS

spectral line A bright or dark line in a spectrum at a specific wavelength produced by the absorption or emission of light by certain atoms. (p. 94)

transits of Venus Rare occasions in the orbit of Venus when it passes between Earth and the Sun and can be seen as a tiny dot directly between Earth and the Sun. (p. 94)

density Mass per volume. (p. 95)

atom The smallest unit of a chemical element, consisting of a nucleus containing protons and neutrons plus a surrounding cloud of electrons. (p. 95)

nucleus The central core of an atom containing protons and neutrons that carries a net positive charge. (p. 95)

proton A positively charged atomic particle contained in the nucleus of an atom. The nucleus of a hydrogen atom consists of a single proton. (p. 95)

neutron An atomic particle contained in the nucleus, with no charge and about the same mass as a proton. (p. 95)

electron Low-mass atomic particle carrying a negative charge. (p. 95)

molecule Two or more atoms bonded together. (p. 96)

heat Total energy stored in a material as agitation among its particles. (p. 96)

temperature A measure of the average agitation among the atoms and molecules of a material. (p. 96)

Kelvin temperature scale A temperature scale starting at absolute zero (−273°C). A one Kelvin change equals a one degree Celsius change. (p. 96)

absolute zero The theoretical lowest possible temperature at which a material contains no extractable heat energy. Zero on the Kelvin temperature scale. (p. 96)

blackbody radiation Radiation emitted by a hypothetical perfect radiator. The spectrum is continuous, and the wavelength of maximum emission depends on the blackbody's temperature. (p. 96)

wavelength of maximum intensity The wavelength at which a perfect radiator emits the maximum amount of energy; it depends only on the object's temperature. (p. 96)

Wien's law A law stating that the hotter a glowing object is, the shorter will be its wavelength of maximum intensity, inversely proportional to its temperature. (p. 96)

Stefan–Boltzmann law A law stating that hotter objects emit more energy than cooler objects of the same size, in proportion to the fourth power of temperature. (p. 96)

photosphere The bright visible surface of the Sun. (p. 97)

sunspot Relatively cooler, dark spot on the Sun that contains intense magnetic fields. (p. 98)

granulation The fine structure of bright regions (grains) with dark edges covering the Sun's surface. (p. 98)

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convection Circulation in a fluid driven by heat. Hot material rises and cool material sinks. (p. 98)

Coulomb force The electrostatic force of repulsion between like charges or attraction between opposite charges. (p. 99)

ion An atom that has lost or gained one or more electrons. (p. 99)

ionization The process in which atoms lose or gain electrons. (p. 99)

binding energy The energy needed to pull an electron away from its atom. (p. 99)

quantum mechanics The study of the behaviour of atoms and atomic particles. (p. 99)

permitted orbit One of the unique orbits that an electron may occupy in an atom. (p. 100)

isotopes Atoms that have the same number of protons but a different number of neutrons. (p. 100)

energy level One of the rungs of the ladder of allowed energy states an electron may occupy in an atom. (p. 100)

excited atom An atom in which an electron has moved from a lower to a higher energy level. (p. 100)

ground state The lowest energy level an electron can occupy in an atom. (p. 101)

quantum leaps Jumps of electrons from one orbit or energy state to another. (p. 101)

Doppler effect The observed change in the wavelength of radiation due to a source moving toward or away from the observer. (p. 101)

blueshift A Doppler shift toward shorter wavelengths caused by a source approaching the observer. The faster the source approaches, the larger the blueshift. (p. 102)

redshift A Doppler shift toward longer wavelengths caused by a source receding from the observer. The faster the source recedes, the larger the redshift. (p. 102)

radial velocity (V_r) The component of an object's velocity that is directed directly away from or toward Earth. (p. 102)

continuous spectrum A spectrum in which there are no absorption or emission lines. (p. 104)

absorption spectrum (dark-line spectrum) A spectrum that contains absorption lines. (p. 104)

absorption line A dark line in a spectrum produced by the absence of photons absorbed by atoms or molecules. (p. 104)

emission spectrum (bright-line spectrum) A spectrum produced by photons emitted by an excited gas. (p. 104)

emission line A bright line in a spectrum caused by the emission of photons from atoms. (p. 104)

Kirchhoff's laws A set of laws that describe the absorption and emission of light by matter. (p. 104)

transition The movement of an electron from one atomic energy level to another. (p. 105)

Lyman series Spectral lines in the ultraviolet spectrum of hydrogen, produced by transitions whose lowest energy level is the ground state. (p. 105)

Balmer series A series of spectral lines produced by hydrogen in the near-ultraviolet and visible parts of the spectrum. The three longest-wavelength Balmer lines are visible to the human eye. (p. 105)

Paschen series Spectral lines in the infrared spectrum of hydrogen produced by transitions whose lowest energy level is the third. (p. 105)

chromosphere Bright gases just above the photosphere of the Sun. (p. 106)

corona The faint outer atmosphere of the Sun, composed of low-density, high-temperature gas. (p. 107)

filtergram A photograph (usually of the Sun) taken in the light of a specific region of the spectrum; for example, an H_α filtergram. (p. 108)

filament A solar eruption, seen from above, silhouetted against the bright photosphere. (p. 108)

spicule A small, flamelike projection in the chromosphere of the Sun. (p. 108)

coronagraph A telescope designed to capture images of faint objects, such as the corona of the Sun, that are near relatively bright objects. (p. 108)

magnetic carpet The network of small magnetic loops that covers the solar surface. (p. 109)

solar wind Rapidly moving atoms and ions that escape from the solar corona and blow outward through the solar system. (p. 109)

helioseismology The study of the interior of the Sun by the analysis of its modes of vibration. (p. 111)

differential rotation The rotation of a body in which different parts of the body have different periods of rotation. This is true of the Sun, the Jovian planets, and the disk of the galaxy. (p. 111)

dynamo effect The process by which a rotating, convecting body of conducting matter, such as Earth's core, can generate a magnetic field. (p. 111)

convective zone The region inside a star where energy is carried outward as rising hot gas and sinking cool gas. (p. 111)

Maunder butterfly diagram A graph showing the latitude of sunspots versus time; first plotted by W. W. Maunder in 1904. (p. 112)

Zeeman effect The splitting of spectral lines into multiple components when the atoms are in a magnetic field. (p. 113)

Maunder minimum A period between 1645 and 1715 of less numerous sunspots and other solar activity. (p. 113)

active region A magnetic region on the solar surface that includes sunspots, prominences, flares, and the like. (p. 113)

prominence Eruption on the solar surface that is visible during total solar eclipses. (p. 116)

flare A violent eruption on the Sun's surface. (p. 117)

reconnection events On the Sun, the merging of magnetic fields to release energy in the form of flares. (p. 117)

aurora The glowing light display that results when a planet's magnetic field guides charged particles toward the north and south magnetic poles, where they strike the upper atmosphere and excite atoms to emit photons. (p. 117)

coronal mass ejection (CME) Matter ejected from the Sun's corona in powerful surges guided by magnetic fields. (p. 117)

coronal hole An area of the solar surface that is dark at X-ray wavelengths; thought to be associated with divergent magnetic fields and the source of the solar wind. (p. 117)

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NOTES

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The Family of Stars

TOPIC SUMMARIES

6.1 Star Distances

How far away are the stars?

- Distance is critical in astronomy. Finding the luminosities, diameters, and masses of stars requires first finding their distances.
- Astronomers can measure the distance to nearby stars by observing their parallaxes. Stellar distances are commonly expressed in light-years and parsecs. In this textbook, we have chosen to use light-years because conceptually it is the simpler of the two options. A light-year (ly) is the distance light travels in one year. One parsec is 206 265 AU—the distance to an imaginary star whose parallax is 1 arc second.
- Stars farther away than about 550 ly have parallaxes too small to measure from ground-based observatories.

6.2 Apparent Brightness, Intrinsic Brightness, and Luminosity

How much energy do stars emit?

- Once you know the distance to a star, you can find its intrinsic brightness, which can be expressed as its absolute magnitude. The absolute magnitude of a star equals the apparent magnitude it would have if it were 33 ly away.
- The luminosity of a star, which can be found from its absolute magnitude, is a measure of the total energy radiated by the star. Luminosity can be expressed in watts, but luminosities of stars are often given in units of the luminosity of the Sun.

6.3 Star Temperatures

How can you tell a star's temperature using its spectrum?

- The hydrogen Balmer lines are weak in cool stars because atoms are not excited out of the ground state. In hot stars, the Balmer lines are weak because atoms are excited to higher orbits or are ionized. Only at intermediate temperatures are the Balmer lines strong.
- The strengths of many spectral lines in a star's spectrum can be used to tell you its temperature. Stars are classified in the temperature spectral sequence: O, B, A, F, G, K, M.
- Long after the spectral sequence was created, astronomers discovered L and T objects with temperatures even cooler than the M stars.

6.4 Star Sizes

How big are stars?

- The H–R diagram is a plot of luminosity versus surface temperature. It is an important graph in astronomy because it sorts the stars into categories by size.
- Roughly 90 percent of normal stars, including the Sun, fall on the main sequence, with the hotter main-sequence stars being more luminous. The giants and supergiants, however, are much larger and lie above the main sequence in the diagram. Some of the white dwarfs are hot stars, but they fall below the main sequence because they are so small.
- The large size of the giants and supergiants means their atmospheres have low densities. Giant stars, luminosity class III, have narrow spectral lines, and supergiants, class I, have extremely narrow lines. Class V main-sequence stars have relatively broad spectral lines.
- Stars so far away that their parallaxes are too small to measure can have their distances estimated by the technique of spectroscopic parallax.

6.5 Star Masses: Binary Stars

How much matter do stars contain?

- The only direct way you can find the mass of a star is by studying binary stars. When two stars orbit a common centre of mass, astronomers find their masses by observing the period and sizes of their orbits.

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- Few binary star systems are easy to analyze; most are spectroscopic binaries in which the component stars are known only by the alternating Doppler shifts of their spectral lines.
- Eclipsing binary star systems allow measurement not just of the component stars' masses but also independent checks on their temperatures and diameters.

6.6 Typical Stars

What is the typical star like?

- Given the mass and diameter of a star, you can find its average density. On the main sequence, the stars are about as dense as the Sun, but the giants and supergiants are very low-density stars. Some are much thinner than air. The white dwarfs, lying below the main sequence, are tremendously dense.
- The mass–luminosity relation says that the more massive a main sequence star is, the more luminous it is. Giants and supergiants do not follow this relation in general, and white dwarfs not at all.
- A survey of stars in the neighbourhood of the Sun shows that giants and supergiants are rare and that red dwarfs, stars at the low-luminosity end of the main sequence, are the most common type, but also faint and hard to find.

KEY TERMS

stellar parallax (*p*) The small apparent shift in position of a nearby star relative to distant background objects due to Earth's orbital motion. (p. 122)

parsec (pc) The distance to a hypothetical star whose parallax is 1 arc second. (p. 123)

intrinsic brightness A measure of the amount of light a star produces. (p. 124)

flux A measure of the flow of energy out of a surface; usually applied to light. (p. 124)

absolute visual magnitude (M_v) Intrinsic brightness of a star. The apparent visual magnitude the star would have if it were 33 ly away. (p. 124)

luminosity (*L*) The total amount of energy a star radiates per second at all wavelengths. (p. 125)

spectral class A star's position in the temperature classification system O, B, A, F, G, K, M, based on the appearance of the star's spectrum. (p. 126)

spectral sequence The arrangement of spectral classes (O, B, A, F, G, K, M) ranging from hot to cool. (p. 127)

L dwarf, T dwarf Spectral classes of brown dwarf stars with lower surface temperatures and luminosities than M dwarfs. (p. 127)

brown dwarf A very cool, low-luminosity star whose mass is not sufficient to ignite nuclear fusion. (p. 127)

Y dwarf A substellar object with temperature below 500 K, having inferred properties intermediate between brown dwarfs and Jovian planets. (p. 128)

Hertzsprung–Russell (H–R) diagram A plot of the intrinsic brightness versus the surface temperature of stars. It separates the effects of temperature and surface area on stellar luminosity. (p. 129)

main sequence The region of the H–R diagram running from upper left to lower right, which includes roughly 90 percent of all stars generating energy by nuclear fusion. (p. 131)

giant A large, cool, highly luminous star in the upper right of the H–R diagram, typically 10 to 100 times the diameter of the Sun. (p. 131)

supergiant An exceptionally luminous star whose diameter is 100 to 1000 times that of the Sun. (p. 131)

red dwarf A faint, cool, low-mass, main-sequence star. (p. 131)

white dwarf A dying star at the lower left of the H–R diagram that has collapsed to the size of Earth and is slowly cooling off. (p. 131)

luminosity class A category of stars of similar luminosity, determined by the widths of lines in their spectra. (p. 132)

spectroscopic parallax The method of determining a star's distance by comparing its apparent magnitude with its absolute magnitude as estimated from its spectrum. (p. 132)

binary stars Pairs of stars that orbit around their common centre of mass. (p. 132)

visual binary system A binary star system in which the two stars are separately visible in the telescope. (p. 134)

spectroscopic binary system A star system in which the stars are too close together to be visible separately. We see a single point of light, and only by taking a spectrum can we determine that there are two stars. (p. 134)

eclipsing binary system A binary star system in which the stars cross in front of each other as seen from Earth. (p. 136)

light curve A graph of brightness versus time commonly used in analyzing variable stars and eclipsing binaries. (p. 136)

mass–luminosity relation The more massive a main-sequence star is, the more luminous it is. (p. 137)

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The Structure and Formation of Stars

TOPIC SUMMARIES

7.1 Models of Stellar Structure

What are the insides of stars like?

- For a star to be stable, it must maintain hydrostatic equilibrium, and the deep layers must be hotter and denser and have higher pressure than the less-deep layers.
- Energy in a star must flow from the hot interior to the cool exterior by conduction, convection, or radiation. Conduction is not usually important inside stars, while the roles of convection and radiation depend on the mass of the star.
- Much of what astronomers know about stars is based on detailed mathematical models of the interior of stars.

7.2 Nuclear Fusion in the Sun and Stars

How do stars generate energy?

- Stars generate energy near their centres, where the densities and temperatures are high enough to allow nuclear fusion reactions to combine hydrogen nuclei to make helium nuclei.
- Energy generated in a star's core flows outward either as photons moving through a radiative zone or as rising currents of hot gas and sinking currents of cool gas in a convective zone.
- Stars of the Sun's mass or less generate energy via the proton–proton chain; more massive main-sequence stars fuse hydrogen into helium in the CNO cycle. These processes generate energy and neutrinos as by-products.
- Older attempts to measure the number of neutrinos coming from the Sun's core found too few of them. More recent measurements have solved this problem by proving that neutrinos change back and forth among three different types called "flavours." The neutrinos confirm that the Sun generates its energy by hydrogen fusion.
- The relationship between pressure and temperature, called the pressure–temperature thermostat, ensures that stars generate just enough energy to be stable.
- Even the most massive stars can generate energy via fusion reactions only until they form iron core. Iron and heavier elements cannot be fused in stars to produce energy.

7.3 Main-Sequence Stars

What determines the properties of main-sequence stars?

- The luminosity of a star depends on its mass. More massive stars have more weight to support, so their pressure–temperature thermostats must make more energy. That makes them more luminous.
- The main sequence has a minimum mass because objects less massive than 0.08 solar masses cannot get hot enough to begin hydrogen fusion.

How long can a star survive?

- The more massive a star is, the faster it uses up its hydrogen fuel. A 25-solar-mass star will exhaust its hydrogen and die in only about 7 million years.

7.4 The Birth of Stars

How are stars born?

- Stars form from the gas and dust of the interstellar medium.
- The interstellar medium can be detected directly, in the form of bright nebulae visible at many different wavelengths of light, and indirectly through the absorption lines in the spectra of distant stars.
- The dust in the interstellar medium makes distant stars look fainter and redder than expected.

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- Molecular clouds are sites of star formation. Such clouds can be triggered to collapse by collision with a shock wave that compresses and fragments the gas cloud, producing a cluster of protostars.

How do you know that theories of star formation are correct?

- A contracting protostar is cooler than a main-sequence star. The dust in the cocoon absorbs the protostar's light and re-radiates it as infrared radiation.
- As a protostar grows hot enough to begin hydrogen fusion at its core, it settles onto the main sequence.
- Very young star clusters contain large numbers of T Tauri stars.
- Some protostars have been found emitting jets of gas. Where these flows strike existing clouds of gas, astronomers can see Herbig–Haro objects. The jets are evidently focused by disks of gas and dust around the protostars.
- The Orion Nebula is a nearby active region of star formation. The bright stars in the centre of the nebula formed within the last few million years. Infrared telescopes detect protostars buried inside the molecular cloud behind the visible nebula.

KEY TERMS

stellar model A table of numbers and associated equations describing the conditions in various layers within a star.

conservation of mass A basic physical law saying that matter cannot be created out of nothing and cannot vanish into nothing. Only its form can change. (p. 144)

conservation of energy One of the basic laws of stellar structure: The total luminosity must equal the sum of energy generated in all of the layers. (p. 144)

energy transport The principle that energy must move from hot to cool regions by conduction, radiation, or convection.

opacity The resistance of a gas to the passage of radiation. (p. 145)

hydrostatic equilibrium One of the basic laws of stellar structure: The weight on each layer must be balanced by the pressure in that layer. (p. 145)

nuclear forces The two forces of nature that govern interactions among particles in the nuclei of atoms. (p. 148)

nuclear fission Reactions that break the nuclei of atoms into fragments. (p. 148)

nuclear fusion Reactions that join the nuclei of atoms to form more massive nuclei. (p. 148)

Coulomb barrier The electrostatic force of repulsion between bodies of like charge, commonly applied to atomic particles. (p. 149)

proton–proton chain A series of three nuclear reactions that build a helium atom by adding together protons; the main energy source in the Sun. (p. 149)

deuterium An isotope of hydrogen in which the nucleus contains a proton and a neutron. (p. 150)

positron The antimatter equivalent of the electron; it has all the same properties as the electron except that its charge is positive instead of negative. (p. 150)

neutrino A neutral, nearly massless atomic particle that travels near the speed of light. (p. 150)

CNO (carbon–nitrogen–oxygen) cycle A series of nuclear reactions that use carbon as a catalyst to combine four hydrogen nuclei to make one helium nucleus plus energy; effective in stars more massive than the Sun. (p. 150)

zero-age main sequence (ZAMS) The location in the H–R diagram where stars first reach stability as hydrogen-burning stars. (p. 153)

interstellar medium (ISM) The gas and dust distributed between the stars. (p. 154)

interstellar dust Microscopic solid grains in the interstellar medium. (p. 155)

nebula A relatively dense cloud of interstellar gas and dust. (p. 155)

interstellar reddening The process in which dust scatters blue light out of starlight and makes the stars look redder. (p. 155)

molecular cloud A dense interstellar gas cloud in which atoms are able to link together to form molecules such as H2 and CO. (p. 159)

shock wave A sudden change in pressure that travels as an intense sound wave. (p. 159)

star cluster A group of stars that formed together and orbit a common centre of mass. (p. 160)

stellar association A group of stars that formed together but are not gravitationally bound to one another. (p. 160)

protostar A collapsing cloud of gas and dust destined to become a star. (p. 160)

Bok globule Small, dark cloud only about 1 ly in diameter that contains 10 to 1000 solar masses of gas and dust, thought to be related to star formation. (p. 161)

Herbig–Haro object A small nebula that varies irregularly in brightness, produced when protostellar jets slam into the surrounding ISM. (p. 161)

T Tauri star A young star surrounded by gas and dust, understood to be contracting toward the main sequence. (p. 161)

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The Deaths of Stars

TOPIC SUMMARIES

8.1 The Beginning of the End

What happens to a star when it uses up the last of the hydrogen fuel in its core?

- As a star uses up the last of its hydrogen, the nuclear reactions die down, and the core contracts, heats up, and forms a hydrogen-fusion shell. Energy flowing from the hydrogen-fusion shell swells the star into a cool giant or a supergiant.
- Eventually, contraction of the star's core ignites helium, first in the core and later in a shell. Massive stars can eventually fuse carbon and other elements.
- H–R diagrams demonstrate how stars in a cluster begin their evolution at the same time but evolve at different rates, depending on their masses.

8.2 The Final End of a Low-Mass Star

How will the Sun and stars smaller than the Sun die?

- Red dwarfs less massive than 0.4 solar mass have very little hydrogen left when they die. They cannot become giant stars and will remain on the main sequence for a great amount of time.
- Slightly heavier stars and those with masses up to about 4 solar masses produce planetary nebulae and then become white dwarfs.
- White dwarfs are the collapsed, exposed cores of sunlike stars, supported against their own gravity by a quantum mechanical phenomenon called electron degeneracy pressure.

8.3 The Evolution of Binary Systems

What happens if an evolving star is in a binary star system?

- Mass can transfer in a binary system through accretion disks around receiving stars. Hot accretion disks can emit light and X-rays.
- Mass transferred onto a white dwarf can build and erupt as a nova explosion. As long as mass transfers form new layers of fuel, eruptions can occur repeatedly.
- A type Ia supernova can occur when mass transferred onto a white dwarf increases its mass above the Chandrasekhar limit, collapses, and immediately fuses its remaining nuclear fuel.

8.4 The Deaths of Massive Stars

How do massive stars die?

- The massive stars on the upper main sequence fuse nuclear fuels up to iron.
- Iron has one of the most tightly bound nuclei of all atoms, and therefore consumes rather than produces energy when fused with other nuclei.
- Once a massive star forms an iron core, the iron core collapses. The remainder of the star falls inward and rebounds from the collapsed core, producing a type II supernova.

8.5 Neutron Stars

What are neutron stars, and how do you know they really exist?

- Because the core of a dying massive star exceeds the Chandrasekhar limit, it cannot form a white dwarf. If its mass lies between 1.4 solar masses and about 3 solar masses, it can halt its contraction and form a neutron star.
- A neutron star is supported by degenerate neutron pressure. Theory predicts that a neutron star should spin very fast, have a surface temperature of millions of degrees K, and have a powerful magnetic field.
- If the powerful beams emitted by neutron stars happen to sweep past Earth as the neutron star spins, we perceive the neutron star as a pulsar.
- The pulsars found in binary systems allow astronomers to estimate the masses of neutron stars.

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8.6 Black Holes and Relativity

What are black holes, and how do you know they really exist?

- Einstein's special theory of relativity tells us how to describe phenomena occurring in reference frames in motion relative to one another.
- For objects travelling at speeds far below the speed of light, special relativity reproduces our ordinary ways of thinking about motion, space, and time. However, at speeds approaching the speed of light, special relativity predicts many strange phenomena, such as time dilation, that have been experimentally verified.
- Special relativity unites space and time into a single entity called space-time. General relativity replaces Newton's law of gravity with a model in which matter tells space-time how to curve and curved space-time tells matter how to move.
- Black holes occur when the collapsing core of a supernova greater than 3 solar masses contracts to such a small size that no light can escape. Black holes can be thought of as regions of extreme space-time curvature.
- There are two relativistic effects on an object falling into a black hole. Compared to the observer, the object's clock would slow and light would be redshifted. The object would heat and deform from powerful tidal forces.
- Binary star systems where mass flows into a compact object with mass greater than 3 solar masses and emits X-rays indicate possible black holes.
- Black holes and neutron stars at the centre of accretion disks can eject powerful beams of radiation and gas. Such beams have been detected.
- Gamma-ray bursts appear to be related to violent events involving neutron stars and black holes. The merging of binary compact objects or shifts in neutron star crusts may produce short bursts.

8.7 Gravitational Waves

- Compact objects orbiting one another produce ripples in the fabric of space-time called gravitational waves. Measurement of these waves gives powerful evidence for our theories of how compact objects, such as neutron stars and black holes, evolve and ultimately contribute to the evolution of the universe.

KEY TERMS

nova From the Latin, meaning "new," a sudden and temporary brightening of a star, making it appear as a new star in the sky; evidently caused by an explosion of nuclear fuel on the surface of a white dwarf. (p. 168)

supernova A "new star" in the sky that is up to 50 000 times more luminous than a normal nova and longer lasting; evidently the result of an explosion of a star.

giant star Large, cool, highly luminous star in the upper right corner of the H–R diagram, typically 10 to 100 times the diameter of the Sun. (p. 168)

red giant A very large, very luminous star in the late stages of its evolution. Intense fusion in shells causes the outer layers to puff up, cool down, and appear red.

supergiant star Exceptionally luminous star whose diameter is 100 to 1000 times that of the Sun. (p. 168)

horizontal branch The location in the H–R diagram of giant stars that are fusing helium in their cores. (p. 169)

planetary nebula An expanding shell of gas ejected from a medium-mass star during the latter stages of its evolution. (p. 171)

degenerate matter Extremely high-density matter in which pressure no longer depends on temperature due to quantum mechanical effects. (p. 172)

compact object One of the three final states of stellar evolution, which generates no nuclear energy and is much smaller and denser than a normal star. (p. 172)

Chandrasekhar limit The maximum mass of a white dwarf, about 1.4 solar masses. A white dwarf of greater mass cannot support itself and will collapse. (p. 173)

Roche lobe The teardrop-shaped volume of space a star controls gravitationally within a binary system. (p. 176)

angular momentum A measure of the tendency of a rotating body to continue rotating. (p. 176)

accretion disk The rotating disk that forms in some situations as matter is drawn gravitationally toward a central body.

type I supernova A supernova explosion that displays no hydrogen lines in its spectrum. It can be the explosion of a white dwarf star or a massive star whose hydrogen-rich outer layers have been previously removed.

type II supernova A supernova explosion caused by the collapse of a massive star, showing prominent hydrogen spectral lines.

supernova remnant The expanding shell of gas and dust marking the site of a supernova explosion. (p. 181)

neutron star A small, highly dense star, with radius about 10 km, composed almost entirely of tightly packed neutrons. (p. 183)

pulsar A source of short, precisely timed radio bursts, understood to be spinning neutron stars. (p. 185)

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lighthouse model The explanation of a pulsar as a spinning neutron star sweeping beams of electromagnetic radiation around the sky. (p. 185)

time dilation The slowing of moving clocks or clocks in strong gravitational fields.

general theory of relativity Einstein's theory describing how space and time are bound together into "space-time."

black hole A mass that has collapsed to such a high density that its gravity prevents the escape of all matter and energy from a large volume of space around it.

singularity An object of zero radius and infinite density. (p. 189)

event horizon The boundary of the region of a black hole from which no radiation may escape. No event that occurs within the event horizon is visible to a distant observer. (p. 190)

Schwarzschild radius (R_S) The radius of the event horizon around a black hole. (p. 190)

gravitational redshift The lengthening of the wavelength of a photon as it escapes from a region of curved space-time gravitational redshift. (p. 191)

gamma-ray burst A sudden, powerful burst of gamma rays. (p. 193)

hypernova Produced when a very massive star collapses into a black hole; a possible source of gamma-ray bursts. (p. 193)

gravitational waves Ripples in the fabric of space-time caused by the motion of objects with mass. They move outward from their source at the speed of light.

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The Milky Way Galaxy

TOPIC SUMMARIES

9.1 The Discovery of the Galaxy

How do you know you live in a galaxy?

- The hazy band of the Milky Way is our wheel-shaped galaxy seen from within, but its size and shape are not obvious. William and Caroline Herschel counted stars over the sky to show that it seemed to be shaped like a disk with the Sun near the centre, but they could not see very far into space because of interstellar gas and dust.
- In the early 20th century, Harlow Shapley calibrated Cepheid variable stars to find the distance to globular clusters and demonstrated that our galaxy is much larger than the part you can see easily and that the Sun is not at the centre.
- Modern observations suggest that our galaxy contains a disk component about 80 000 ly in diameter and the Sun is two-thirds of the way from the centre to the visible edge. The central bulge and an extensive halo that contains old stars and a small amount of gas and dust make up the spherical component.
- The mass of the galaxy can be found from its rotation curve. Kepler's third law tells astronomers the galaxy contains over 100 billion solar masses, and the rising rotation curve at great distance from the centre shows that the halo must contain much more mass. Because that material is not emitting detectable electromagnetic radiation, astronomers call it dark matter.

9.2 Spiral Arms and Star Formation

How do you know ours is a spiral galaxy, and what are the spiral arms?

- The most massive stars live such short lives that they don't have time to move from their place of birth. Because they are concentrated along the spiral arms, astronomers conclude that the spiral arms are sites of star formation.
- Spiral arms can be traced through the Sun's neighbourhood by using spiral tracers such as O and B stars, but to extend the map over the entire galaxy astronomers must use infrared and radio observations to see through the gas and dust.
- The spiral density wave theory suggests that the spiral arms are regions of compression that move around the disk. When an orbiting gas cloud overtakes the compression wave, the gas cloud forms stars. Another process, self-sustaining star formation, may modify the spiral arms with branches and spurs; this happens when the birth of massive stars triggers the formation of more stars by compressing neighbouring gas clouds.

9.3 The Origin and History of the Milky Way

How did our galaxy form and evolve?

- The oldest open star clusters indicate that the disk of our galaxy is only about 9 billion years old. The oldest globular clusters appear to be at least 13 billion years old, so our galaxy must have begun forming at least 13 billion years ago.
- Stellar populations are an important clue to the formation of our galaxy. The first stars to form in our galaxy, termed population II stars, were poor in elements heavier than helium: elements that astronomers call metals. As generations of stars manufactured metals and spread them back into the interstellar medium, the metal abundance of more recent generations increased. Population I stars, including the Sun, are richer in metals than population II stars.
- Because the halo is made up of population II stars and the disk is made up of population I stars, astronomers conclude that the halo formed first and the disk later. The monolithic collapse model, that the galaxy formed from a single, roughly spherical cloud of turbulent gas and gradually flattened into a disk, has been amended to include mergers with other galaxies and later infalling gas contributing to the disk.

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9.4 The Nucleus

What lies at the very centre of our galaxy?

- The nucleus of the galaxy is not visible at visual wavelengths, but radio, infrared, and X-ray radiation can penetrate the gas and dust in space. These wavelengths reveal crowded central stars and warmed dust.
- The very centre of the Milky Way Galaxy is marked by a radio source, Sagittarius A*. The source must be less than a few astronomical units in diameter, but the motion of stars around the centre shows that it must contain roughly 4.3 million solar masses. A supermassive black hole is the only object that could contain so much mass in such a small space.

KEY TERMS

Cepheid variable stars Variable stars with pulsation periods of 1 to 60 days and whose period of variation is related to their luminosity. (p. 204)

instability strip The region of the H–R diagram in which stars are unstable to pulsation. A star evolving through this strip becomes a variable star. (p. 204)

period–luminosity relation The relation between period of pulsation and intrinsic brightness among Cepheid variable stars. (p. 205)

proper motion The rate at which a star moves across the sky, measured in arc seconds per year. (p. 205)

calibrate To make observations of reference objects, checks on instrument performance, calculations of unit conversions, and so on, needed to completely understand measurements of unknown quantities. (p. 206)

disk component All material confined to the plane of the galaxy. (p. 207)

spiral arms Long spiral pattern of bright stars, star clusters, gas, and dust. Spiral arms extend from the centre to the edge of the disk of spiral galaxies. (p. 208)

spherical component The part of the galaxy that includes all matter in a spherical distribution around its centre (the halo and central bulge). (p. 208)

halo The spherical region of a spiral galaxy, containing a thin scattering of stars, star clusters, and small amounts of gas. (p. 208)

central bulge The dense cloud of stars that surrounds the centre of our galaxy. (p. 208)

rotation curve A graph of orbital velocity versus radius in the disk of a galaxy. (p. 210)

dark halo The low-density extension of the halo of our galaxy, believed to be composed of dark matter. (p. 210)

dark matter Nonluminous matter that is detected only by its gravitational influence. (p. 210)

spiral tracer Object used to map the spiral arms—for example, O and B associations, open clusters, clouds of ionized hydrogen, and some types of variable stars. (p. 211)

density wave theory Theory proposed to account for spiral arms as compressions of the interstellar medium in the disk of the galaxy. (p. 212)

self-sustaining star formation The process by which the birth of stars compresses the surrounding gas clouds and triggers the formation of more stars. (p. 213)

population I star Stars rich in atoms heavier than helium; nearly always relatively young stars found in the disk of the galaxy. (p. 214)

population II star Stars poor in atoms heavier than helium; nearly always relatively old stars found in the halo, globular clusters, or the central bulge. (p. 214)

metals In astronomical usage, all atoms heavier than helium. (p. 214)

monolithic collapse model An early hypothesis that says the galaxy formed from the collapse of a single large cloud of turbulent gas over 13 billion years ago. (p. 216)

Sagittarius A* The powerful radio source located at the core of the Milky Way Galaxy. (p. 220)

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Galaxies

TOPIC SUMMARIES

10.1 The Family of Galaxies

What types of galaxies exist?

- Galaxies can be divided into three classes, and their subclasses specify details of the galaxy's shape.
- Elliptical galaxies contain little gas and dust and cannot make new stars. Consequently, they lack hot, blue stars and have a relatively red colour.
- Spiral galaxies contain more gas and dust and support active star formation. The massive, hot, and blue stars give these galaxies a blue colour.
- A spiral galaxy's halo and nuclear bulge usually lack gas and dust and contain little star formation, and so have a red colour.
- Irregular galaxies have no obvious shape but contain gas and dust and support star formation.

10.2 The Distribution of Galaxies in the Universe

How do astronomers measure the distances to galaxies?

- Astronomers find the distance to galaxies using objects of known luminosity, such as Cepheid variable stars and type Ia supernovae explosions.
- Astronomers can estimate the distance to a galaxy by dividing its apparent rate of recession (its radial velocity) by the Hubble constant. Apparent rate of recession is related to distance by the Hubble law.
- Telescopes are time machines. Looking farther in space means looking farther back in time.
- Galaxies are organized in clusters, and clusters in superclusters.

10.3 The Masses of Galaxies and Dark Matter

How do astronomers measure masses of galaxies and clusters of galaxies?

- Astronomers measure the masses of galaxies in several ways. The most precise is the rotation curve method, but this can be applied only to nearby galaxies.
- Observations show that galaxies contain 10 to 100 times more dark matter than visible matter. Signs of dark matter are more obvious in outer halos.
- Estimates of gravitational mass can be done in several ways. The most direct ones are observing galaxies orbiting the massive central elliptical galaxies, and gravitational lensing.
- Masses of clusters of galaxies show even larger discrepancies between visible mass (in all wavelengths) and gravitational mass, which is mass inferred from gravity effects.

10.4 The Evolution of Galaxies

Why are there different kinds of galaxies, and how do galaxies evolve?

- Rich clusters of galaxies contain fewer spirals than do poor clusters of galaxies, and that is evidence that galaxies evolve by collisions and mergers.
- When galaxies collide, tides twist and distort their shapes, and the resulting compression of gas clouds triggers star formation.
- There is clear evidence that our Milky Way Galaxy is devouring some of the small galaxies that orbit nearby and that it has consumed other small galaxies in the past.
- Shells of stars, counter-rotating parts of galaxies, streams of stars in the halos of galaxies, and multiple nuclei are evidence that galaxies can merge.
- The merger of two larger galaxies can scramble star orbits and drive bursts of star formation to use up gas and dust.
- Spiral galaxies have thin, delicate disks and appear not to have suffered mergers with large galaxies.
- A galaxy moving through the gas in a cluster of galaxies can be stripped of its own gas and dust and become an S0 galaxy.

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- At great distances, astronomers see that galaxies were smaller, more irregular, and closer together. Also, there were more spirals and fewer ellipticals long ago.

10.5 Active Galaxies, Quasars, and Supermassive Black Holes

What is the energy source for active galaxies, what can trigger the activity, and what does that reveal about the history of galaxies?

- Seyfert galaxies are spirals with small, highly luminous cores. Spectra of Seyfert galaxy nuclei show that they contain highly excited, rapidly moving gas.
- Quasars have very high redshifts, evidence of great distance. To be visible from so far, quasars must be ultraluminous and provide a window into the time when galaxies were just forming.
- The spectra of hazy objects near quasars and the spectra of quasar fuzz show that quasars are the active cores of very distant galaxies.
- Evidence is strong that AGN contain supermassive black holes into which matter is flowing through hot accretion disks. This can eject jets in opposite directions that push into the intergalactic medium and inflate radio lobes like balloons.
- Stars near the centres of galaxies are orbiting at high velocities, suggesting the presence of supermassive black holes in the centres of most galaxies.
- According to the unified model, what you see depends on the tilt of the accretion disk. Seen face-on, the core produces broad spectral lines. Seen edge-on, the core is hidden and the spectrum contains narrow lines.
- Many galaxies appear to contain dormant supermassive black holes at their centres. Only when a supermassive black hole is fed does it erupt.
- Matter flowing into a hot accretion disk around a black hole can eject high-energy jets of gas and radiation perpendicular to the disk.
- Interactions between galaxies can throw matter into the centre, feed the black hole, and trigger eruptions.
- Supermassive black holes powering AGN and quasars cannot have been formed by dying stars but may have formed as the nuclear bulges of their host galaxies began to form and contract.

KEY TERMS

Large Magellanic Cloud The larger of two irregular galaxies visible in the southern sky passing near the Milky Way Galaxy. (p. 226)

Small Magellanic Cloud The smaller of two irregular galaxies visible in the southern sky passing near the Milky Way Galaxy. (p. 226)

elliptical galaxy A galaxy that is round or elliptical in outline and contains little gas and dust, no disk or spiral arms, and few hot, bright stars. (p. 228)

lenticular galaxy A galaxy with an obvious disk and nuclear bulge but no visible gas and dust and not-hot, bright stars. (p. 228)

irregular galaxy A galaxy with a chaotic appearance, large clouds of gas and dust, and both population I and II stars, but without spiral arms. (p. 228)

spiral galaxy A galaxy with an obvious disk component that contains gas, dust, hot bright stars, and spiral arms. (p. 229)

barred spiral galaxy A spiral galaxy with an elongated nucleus resembling a bar from which the arms originate. (p. 229)

distance ladder The calibration used to build a distance scale extending from the size of Earth to the most distant visible galaxies. (p. 230)

standard candle Object of known brightness that astronomers use to find distance—for example, Cepheid variable stars and supernovae. (p. 231)

Tully-Fisher relationship The linear relation between luminosity and the rotational rate of spiral galaxies used to determine the distance to spiral galaxies as standard candles. (p. 232)

Hubble law The linear relation between the distances to galaxies and the apparent velocity of recession. (p. 233)

Hubble constant A measure of the rate of expansion of the universe; the average value of the apparent velocity of recession divided by distance, about 70 km/s/Mpc. (p. 233)

look-back time The amount by which you look into the past when you look at a distant galaxy; a time that equals the distance to the galaxy in light-years. (p. 233)

rich galaxy cluster A cluster containing 1000 or more galaxies, usually mostly ellipticals, scattered over a volume only a few Mpc in diameter. (p. 234)

poor galaxy cluster An irregularly shaped cluster that contains fewer than 1000 galaxies, many of which are spiral, and no giant ellipticals. (p. 234)

Local Group The small cluster of a few dozen galaxies that contains the Milky Way Galaxy. (p. 234)

rotation curve method A method of determining a galaxy's mass by observing the orbital velocity and orbital radius of stars in the galaxy. (p. 235)

gravitational lensing The curving of light by a large mass when the light passes between the source and the observer. Multiple images of the source can be seen. (p. 237)

tidal tail A long streamer of stars, gas, and dust torn from a galaxy during its

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close interaction with another passing galaxy. (p. 240)

ring galaxy A galaxy that resembles a ring around a bright nucleus, resulting from a head-on collision between two galaxies. (p. 241)

starburst galaxy A galaxy undergoing a rapid burst of star formation. (p. 241)

active galaxy A galaxy whose centre emits large amounts of excess energy, often in the form of radio emissions. Active galaxies have massive black holes in their centres into which matter is flowing. (p. 243)

active galactic nuclei (AGN) The centres of active galaxies that are emitting large amounts of excess energy. (p. 243)

radio galaxy A galaxy that is a strong source of radio signals. (p. 244)

Seyfert galaxy An otherwise normal spiral galaxy with an unusually bright, small core that fluctuates in brightness. (p. 244)

quasar Small, powerful source of energy in the active core of a very distant galaxy. (p. 247)

unified model An attempt to explain the different types of active galactic nuclei using a single model viewed from different directions. (p. 249)

blazar A type of active galaxy nucleus that is especially variable and has few or no spectral emission lines. (p. 249)

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Cosmology in the 21st Century

TOPIC SUMMARIES

11.1 Introduction to the Universe

Does the universe have an edge and a centre?

- Astronomers conclude that it is impossible for the universe to have an edge because this introduces logical inconsistencies. If the universe has no edge it cannot have a centre.
- The darkness of the night sky leads astronomers to the conclusion that the universe is not infinitely old. If it were infinite in extent and age, every spot on the sky would glow as brightly as the surface of a star. This problem, commonly known as Olbers's paradox, leads to the conclusion that the universe had a beginning.

11.2 The Big Bang Theory

How do you know that the universe began with a big bang?

- Edwin Hubble's 1929 discovery that the redshift of a galaxy is proportional to its distance is known as Hubble's law and indicates that the universe is expanding. Tracing this expansion backward in time brings you to an initial high-density, high-temperature state commonly called the big bang.
- The galaxies do not recede from a single point. They recede from each other as space expands between them.
- The CMB is blackbody radiation with a temperature of about 2.73 K uniformly spread over the entire sky. It is the light from the big bang, released from matter at the time of recombination and now redshifted by a factor of 1100.
- The background radiation is clear evidence that the universe began with a big bang.
- During the first three minutes of the big bang, nuclear fusion converted some of the hydrogen into helium but was unable to make many other heavy atoms because no stable nuclei exist with atomic weights of 5 or 8. Today, hydrogen and helium are common in the universe, but heavier atoms are rare.

11.3 Space and Time, Matter and Energy

How does the universe expand?

- In its major features, the universe is isotropic and homogeneous. It looks the same in all directions and in all locations.
- Isotropy and homogeneity together lead to the cosmological principle: the idea that there are no special places in the universe. Except for local differences, every place is the same.
- General relativity explains that cosmic redshifts are caused by the stretching of photon wavelengths as they travel through expanding space-time.
- Model universes with flat (uncurved) space-time are infinite and can expand forever. A flat universe would have an average density equal to what is called the critical density. Modern observations indicate that the universe is flat.
- The amounts of deuterium and lithium-7 show that normal baryonic matter can make up only about 5 percent of the critical density. Dark matter must be non-baryonic and makes up less than 30 percent of the critical density. For the universe to be flat, there must be another major component aside from baryonic matter and dark matter.

11.4 Modern Cosmology

How has the universe evolved, and what will be its fate?

- The inflationary theory proposes that the universe expanded dramatically a tiny fraction of a second after the big bang.
- Inflation solves the flatness problem because the sudden inflation forced the universe to become flat, just as a spot on an inflating balloon becomes flatter as the balloon inflates.
- Inflation solves the horizon problem because the part of the universe that is now observable was so small before inflation that energy could move and equalize the temperature everywhere.

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- Observations of type Ia supernovae reveal that the expansion of the universe is speeding up. This is thought to be due to "dark energy."
- The nature of dark energy is unknown. It may be described by Einstein's cosmological constant, or it may change with time, in which case astronomers refer to it as quintessence.
- Astronomers have observed gravitational waves using the two LIGO detectors. This gives them a new way of studying strong gravitational interactions and the nature of the cosmological constant.
- The observed value of the Hubble constant implies that the universe is 13.8 billion years old. The future fate of the universe depends on the nature of dark energy. If dark energy increases in strength with time, the universe could end in a big rip.
- The sudden inflation of the universe could have magnified tiny quantum mechanical fluctuations in space-time. These very large-scale but weak differences in gravity worked with dark matter to draw together baryonic (ordinary) matter and create the large-scale structure.
- Precise observations of irregularities in the CMB and in the large-scale structure of the universe confirm that the universe is flat and contains about 4.9 percent baryonic matter, 26.8 percent dark matter, and 68.3 percent dark energy.
- The Large Hadron Collider (LHC), the largest experiment in history, produces and smashes together beams of fundamental particles with energies high enough to recreate conditions of the big bang. The LHC experiments will give us insight into the fundamental forces, the origin of mass, extra dimensions of space, microscopic black holes, and the nature of dark matter.

KEY TERMS

cosmology The study of the nature, origin, and evolution of the universe. (p. 252)

Olbers's paradox The conflict between theory and evidence regarding the darkness of the night sky. (p. 254)

observable universe The part of the universe that you can see from your location in space and in time. (p. 255)

big bang The high-density, high-temperature state from which the expanding universe of galaxies began. (p. 256)

Hubble time The age of the universe, equivalent to 1 divided by the Hubble constant. The Hubble time is the age of the universe based on its expansion at a constant rate since the big bang. (p. 256)

cosmic microwave background (CMB) Radiation from the hot matter of the universe soon after the big bang. The large redshift makes it appear to come from a blackbody with a temperature of 2.7 K. (p. 257)

antimatter Matter composed of antiparticles, which upon colliding with a matching particle of normal matter, annihilates, converting the mass of both particles into energy. In comparison to the corresponding particles of normal matter, antiparticles have the same mass but opposite charge. (p. 262)

recombination The stage, within 400 000 years of the big bang, when neutral hydrogen formed and the gas became transparent to radiation. (p. 263)

dark age The period of time after the glow of the big bang faded into the infrared and before the birth of the first stars, during which the universe expanded in darkness. (p. 263)

reionization The stage in the early history of the universe when ultraviolet photons from the first stars ionized the gas that filled space. (p. 263)

isotropy The observation that, in its general properties, the universe looks the same in every direction. (p. 264)

homogeneity The observation that, on the large scale, matter is uniformly spread through the universe. (p. 264)

cosmological principle The assumption that any observer in any galaxy sees the same general features of the universe. (p. 264)

open universe A model of the universe in which space-time is curved in such a way that the universe is infinite. (p. 265)

closed universe A model of the universe in which space-time is curved to meet itself, and the universe is finite. (p. 265)

flat universe A model of the universe in which space-time is not curved. (p. 265)

critical density The average density of matter and energy in the universe needed to make its curvature flat. (p. 266)

nonbaryonic matter Proposed dark matter made up of particles other than protons and neutrons (baryons). (p. 266)

cold dark matter Dark matter that is made of slow-moving particles. (p. 267)

flatness problem The peculiar circumstance that the early universe must have contained almost exactly the right amount of matter to make space-time flat. (p. 267)

horizon problem The circumstance that the primordial background radiation seems much more isotropic than can be explained by the standard big bang theory. (p. 267)

inflationary big bang A version of the big bang theory, derived from grand unified theories of particle physics, that includes a rapid expansion when the universe was very young. (p. 268)

cosmological constant A constant in Einstein's equations of space and time that represents a force of repulsion. (p. 269)

quintessence A possible form of dark energy that can change in strength as the universe ages. (p. 269)

dark energy The energy believed to drive the acceleration of the expanding universe. (p. 270)

big rip The fate of the universe if dark energy increases with time, and galaxies, stars, and even atoms are eventually ripped apart by the accelerating expansion of the universe. (p. 271)

large-scale structure The distribution of clusters and superclusters of galaxies in filaments and walls enclosing voids. (p. 273)

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Planet Formation and Exoplanets

TOPIC SUMMARIES

12.1 The Great Chain of Origins

What theory explains the origin of the solar system?

- Modern astronomy reveals that the matter in our solar system was formed in the big bang, and the atoms heavier than helium were created in successive generations of stars. The Sun and planets evidently formed from a cloud of gas in the interstellar medium.
- Hot disks of gas and dust have been detected around young stars and are understood to be where planets could form.
- The solar nebula theory proposes that the planets formed in a disk of gas and dust around the protostar that became the Sun.

12.2 A Survey of the Planets

What observed properties of the solar system must be explained by the theory of its origin?

- The solar system is disk shaped. The orbital revolutions of the planets, as well as most of their axial rotations and most of the orbits of their moons, share a common direction of motion.
- The planets are divided into two types: Terrestrial planets and Jovian planets.
- The Jovian worlds have gaseous surfaces, ring systems, and large families of moons. The Terrestrial planets are denser, have rocky surfaces, and have no rings and few moons.

12.3 Space Debris: Asteroids, Comets, and Meteoroids

What are asteroids and comets and what are their connections to meteors and meteorites?

- Asteroids are rocky, irregular in shape and heavily cratered by collisions. Most asteroids lie in a belt between Mars and Jupiter, although some follow orbits that cross into the inner solar system.
- Comets are icy bodies that fall into the inner solar system along long elliptical orbits.
- A comet gas tail is ionized gas carried away by the solar wind. A comet dust tail is solid debris released from the nucleus and blown outward by the pressure of sunlight.
- Meteoroids that fall into Earth's atmosphere are vaporized by friction and become visible as meteors. Meteoroids that reach the ground are called meteorites.
- Evidence suggests that most meteorites are fragments of asteroids. The vast majority of meteors appear to be bits of debris from comets.

12.4 The Story of Planet Formation

How do planets form?

- The age of a rocky body can be found by radioactive dating. The oldest objects in our solar system are some meteorites that have ages of 4.6 billion years. This is taken to be the age of the solar system.
- Planets begin growing by accreting solid material. But once a planet approaches about 15 Earth masses, it can begin growing by gravitational collapse as it pulls in gas from the solar nebula.
- The condensation sequence explains that the Terrestrial planets formed in the inner solar system where only denser minerals could condense to form solids, while the Jovian planets formed farther out where ices could condense.
- The Terrestrial planets may have formed slowly from the accretion of planetesimals of similar composition and then differentiated later when radioactive decay heated the planet's interiors.
- Earth's first atmosphere was outgassed.
- The asteroids formed as rocky planetesimals between Mars and Jupiter, but Jupiter prevented them from forming a planet.
- Comets are the leftover icy planetesimals in the outer solar system; comets falling in from the Oort cloud become long-period comets.

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- Other icy bodies in the outer solar system make up the Kuiper belt. Objects from the Kuiper belt can become short-period comets.
- All the old surfaces in the solar system were heavily cratered by an early bombardment of debris that filled the solar system when it was young.

12.5 Planet-Forming Disks Around Young Stars

What is the observational evidence for our models of planet formation?

- Telescopes operating at submillimetre and far-infrared wavelengths can image protoplanetary disks of cold dust and gas around very young stars.
- These disks show characteristic rings and gaps believed to be caused by gravitational interactions between the disks and planets forming within them.
- Slightly older stars are often orbited by debris disks, which consist of dust and small particles released during planet-forming collisions or left over from protoplanetary disks.
- Observations of protoplanetary and debris disks offer strong confirmation of the nebular theory of planet formation.

12.6 Exoplanets: Planets Orbiting Other Stars

How can we find planets in other solar systems?

- Direct imaging of exoplanets is extremely difficult because they get lost in the glare of their parent stars. Therefore, most of the methods for detecting exoplanets are indirect.
- The transit method for detecting exoplanets involves watching a star for many years, waiting to detect repeating drops in brightness caused by one or more planets orbiting that star.
- The orbit of a star and its planets around their common centre of mass causes a periodic Doppler shift in the spectrum of the star. The Doppler method of exoplanet detection searches for stars with this characteristic shift.
- Combining all methods of exoplanet detection, more than 4000 exoplanets are now known.
- Many exoplanets orbiting in the habitable zones of their parent stars have been detected, but little is known about their atmospheres. Future telescopes such as JWST will advance our understanding of exoplanet atmospheres.

KEY TERMS

solar nebula theory A theory of formation of the solar system consistent with our current observations that describes how a rotating cloud of gas and dust gravitationally collapsed and flattened into a disk around the Sun forming at the centre, from which the planets were formed. (p. 280)

asteroid Small, rocky world. Most orbit between Mars and Jupiter in the asteroid belt. (p. 282)

comet One of the small, icy bodies that orbit the Sun and produce tails of gas and dust when they approach the Sun. (p. 283)

Terrestrial planet An Earth-like planet—small, dense, rocky. (p. 284)

Jovian planet Jupiter-like planet with a large diameter and low density. (p. 284)

volatile Easily evaporated. (p. 286)

Kuiper belt The collection of icy planetesimals orbiting in a region from just beyond Neptune out to 50 AU or more. (p. 286)

Oort cloud The hypothetical source of comets, a swarm of icy bodies understood to lie in a spherical shell extending to 100 000 AU from the Sun. (p. 286)

meteor A small bit of matter heated by friction to incandescent vapour as it falls into Earth's atmosphere. (p. 287)

meteoroid A meteor in space before it enters Earth's atmosphere. (p. 287)

meteorite A meteor that survives its passage through the atmosphere and strikes the ground. (p. 288)

carbonaceous chondrite Stony meteorite that contains small, glassy spheres—called chondrules—and volatiles. These chondrites may be the least-altered remains of the solar nebula still present in the solar system. (p. 288)

meteor shower A display of meteors that appear to come from one point in the sky; understood to be cometary debris. (p. 288)

half-life The time required for half of the radioactive atoms in a sample to decay. (p. 289)

uncompressed density The density a planet would have if its gravity did not compress it. (p. 291)

ice line A boundary beyond which water vapour could freeze to form ice. (p. 292)

condensation sequence The sequence in which different materials condense from the solar nebula, depending on their distance from the Sun. (p. 292)

planetesimal One of the small bodies that formed from the solar nebula and eventually grew into a protoplanet. (p. 292)

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condensation The growth of a particle by addition of material from surrounding gas, atom by atom. (p. 292)

accretion The sticking together of solid particles to produce a larger particle. (p. 292)

protoplanet Massive object, destined to become a planet, resulting from the coalescence of planetesimals in the solar nebula. (p. 293)

gravitational collapse The process by which a forming body such as a planet gravitationally captures gas rapidly from the surrounding nebula. (p. 293)

differentiation The separation of planetary material inside a planet according to density. (p. 293)

outgassing The release of gases from a planet's interior. (p. 293)

heavy bombardment The intense cratering that occurred sometime during the first 0.5 billion years in the history of the solar system. (p. 295)

NEO (near-Earth object) A small solar system body (asteroid or comet) with an orbit near enough to Earth that it poses some threat of eventual collision. (p. 296)

evolutionary theory An explanation of a phenomenon involving slow, steady processes. (p. 297)

catastrophic theory An explanation of a phenomenon involving special, sudden, perhaps violent, events. (p. 297)

heat of formation In planetology, the heat released by infalling matter during the formation of a planetary body. (p. 297)

debris disk A disk of dust around some stars, found by infrared observations. The dust is debris from collisions among asteroids, comets, and Kuiper belt objects. (p. 298)

exoplanet A planet orbiting a star other than the Sun. (p. 299)

transit method A technique for finding exoplanets by searching for the dimming of their parent stars when the planet passes in front of the star. (p. 300)

Doppler method A technique for finding exoplanets by searching for periodic Doppler shifts in the spectra of stars. The shifts are caused by the star and an unseen planet orbiting their common centre of mass. (p. 301)

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Comparative Planetology of the Terrestrial Planets

TOPIC SUMMARIES

13.1 A Travel Guide to the Terrestrial Planets

How can comparison help you understand the Terrestrial planets?

- The Terrestrial worlds differ mainly in size, but they all have low-density rocky crusts, mantles of dense rock, and metallic cores.
- Comparative planetology alerts you to expect that cratered surfaces are old, that heat flowing out of a planet drives geological activity, and that the nature of a planet's atmosphere depends on both the size of the planet and its temperature.
- Earth's moon illustrates important principles such as cratering and flooding of basins by lava.

13.2 Earth: The Active Planet

What are the main features of Earth when viewed as a planet?

- Earth has passed through three evolutionary stages: (1) differentiation, forming a liquid metallic core that generates a magnetic field; (2) cratering and basin formation; and (3) continued slow surface evolution.
- Earth is dominated by plate tectonics, a process that breaks the crust into moving plates. This process is driven by heat flowing upward from the interior.
- Earth's primary atmosphere was probably mostly carbon dioxide, nitrogen, and water vapour. Most of the carbon dioxide dissolved in seawater and was added to ocean sediments, and plant life has added oxygen to the atmosphere, producing the current secondary atmosphere.
- The greenhouse effect can warm a planet if gases such as carbon dioxide in the atmosphere are transparent to light but opaque to infrared. Measurements of carbon isotope ratios and carbon dioxide versus oxygen abundances make it clear that the CO_2 added to the atmosphere since around 1800 is predominantly from the burning of fossil fuels. Observations and model calculations have eliminated other candidate causes for the current warming, for example natural climate cycles or variations in the Sun's output.

13.3 The Moon

How does size determine the geological activity and evolution of a planetary body?

- Earth's moon formed in a molten state and partly differentiated, but it contains little metal and has a low density.
- Because it is a small world, Earth's moon has lost most of its internal heat and is no longer geologically active. Its old highlands are heavily cratered, but the lowland maria are filled with smooth lava flows that formed soon after the end of the heavy bombardment.
- The large-impact hypothesis suggests the Moon formed when an impact between Earth and a very large planetesimal ejected debris that formed a disk around Earth. The Moon formed from that disk.

13.4 Mercury

How does Mercury compare to Earth?

- Mercury is smaller than Earth but larger than Earth's moon. It is airless and has an old, heavily cratered surface.
- Mercury has a much higher density than Earth's moon and must have a large metallic core. When it was young, Mercury may have suffered a major impact that drove off some of its lower-density crust and mantle rock and left a metallic core that is larger than the condensation sequence would imply.
- Mercury has long curving ridges that were formed by compression of the crust when its large metallic core solidified and contracted.

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13.5 Venus

How do distance from the Sun and planet size affect the properties of its atmosphere?

- Although Venus is almost as big as Earth, it has a thick, cloudy atmosphere of CO_2 that hides the surface. The surface can be studied by radar mapping.
- The CO_2 atmosphere drives an intense greenhouse effect, making Venus's surface hot enough to melt lead.
- Venus is slightly closer to the Sun than Earth and was too warm for liquid water oceans to persist and dissolve carbon dioxide from the atmosphere, so Venus suffered a runaway greenhouse effect.
- The hot crust of Venus is dominated by volcanism, but not by plate tectonics.

13.6 Mars

What is the evidence that surface conditions on Mars were originally more Earth-like than they are at present?

- Mars is about half the diameter of Earth; it has a thin atmosphere and has lost much of its internal heat.
- The loss of atmospheric gases depends on the size of a planet and its temperature. Mars is cold, but it is small and has a low escape velocity, and many of its lighter gases have leaked away.
- Some water may have leaked away because UV radiation from the Sun broke it into hydrogen and oxygen, but some water is frozen in the polar caps and in the soil. Orbiters have also measured large amounts of water frozen below the surface.
- Rovers have found clear signs that liquid water flowed over the surface in at least some places and therefore evidence that the Martian climate was different in the past. The northern lowlands may even have held an ocean once.
- Outflow channels and valley networks are visible from orbit, but water cannot now exist as a liquid on Mars because of its low temperature and low atmospheric pressure.
- The southern hemisphere of Mars is old, cratered terrain, but some large volcanoes lie in the north. The sizes of these volcanoes indicate that the crust does not have horizontal motions and plate tectonics.
- Some volcanism may still occur on Mars, but because the planet is small it has cooled and is not very active geologically.
- The two moons of Mars are probably captured asteroids.

KEY TERMS

comparative planetology Understanding planets by searching for and analyzing contrasts and similarities among them. (p. 306)

mantle The layer of dense rock and metal oxides that lies between the molten core and Earth's surface, or a similar layer in another planet. (p. 309)

primary atmosphere A planet's first atmosphere. (p. 311)

secondary atmosphere A planet's atmosphere that replaces the primary atmosphere—for example by outgassing, impact of volatile-bearing planetesimals, or biological activity. (p. 311)

greenhouse effect The process by which a carbon dioxide atmosphere traps heat and raises the temperature of a planetary surface. (p. 311)

plate tectonics The constant destruction and renewal of Earth's surface by the motion of sections of crust. (p. 312)

global warming The gradual increase in the surface temperature of Earth caused by human modifications to Earth's atmosphere. (p. 314)

maria (mare) Lunar lowlands filled by successive flows of dark lava; from the Latin for *sea*. (p. 316)

albedo The ratio of the amount of light reflected from an object to the amount of light received by the object. Albedo equals 0 for perfectly black and 1 for perfectly white. (p. 316)

ejecta Pulverized rock scattered by meteorite impacts on a planetary surface. (p. 316)

anorthosite Aluminum- and calcium-rich silicate rock found in the lunar highlands. (p. 316)

breccia Rock composed of fragments of older rocks bonded together. (p. 316)

large-impact hypothesis Hypothesis that the Moon formed from debris ejected during a collision between Earth and a large planetesimal. (p. 317)

magma ocean The exterior of the newborn Moon, a shell of molten rock hundreds of kilometres deep. (p. 317)

multiringed basin Large impact feature (crater) containing two or more concentric rims formed by fracturing of the planetary crust. (p. 318)

late heavy bombardment The sudden, temporary increase in the cratering rate in our solar system that occurred about 4 billion years ago. (p. 318)

micrometeorite Meteorite of microscopic size. (p. 318)

runaway greenhouse effect A greenhouse effect so dramatic that it amplifies itself, becoming stronger with time. (p. 321)

coronae On Venus, the large, round geological faults in the crust caused by the intrusion of magma below the crust. (p. 323)

permafrost Permanently frozen soil. (p. 324)

shield volcano Wide, low-profile volcanic cone produced by highly liquid lava. (p. 325)

outflow channel Geological features on Mars and Earth caused by flows of vast amounts of water released suddenly. (p. 327)

valley network A system of dry drainage channels on Mars that resembles the beds of rivers and tributary streams on Earth. (p. 327)

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The Outer Solar System

TOPIC SUMMARIES

14.1 Exploring the Outer Planets

- The Jovian planets—Jupiter, Saturn, Uranus, and Neptune—are large, low-density worlds rich in hydrogen and helium.
- The atmospheres of the Jovian planets are marked by cloud belts parallel to their equators.
- Jupiter and Saturn, usually called "gas giants," are composed mostly of liquid hydrogen with liquid metallic hydrogen in deep regions close to their cores and might instead be called "liquid giants." Uranus and Neptune contain water in liquid and solid form and therefore are sometimes called "ice giants."
- All of the Jovian worlds have large systems of satellites and rings that have had complex histories.

14.2 Jupiter

- Jupiter's atmosphere contains three layers of clouds formed of hydrogen-rich molecules such as ammonia and water.
- The clouds are in bands parallel to the equator called zones and belts. Zones are high-pressure regions of rising gas, and belts are lower-pressure areas of sinking gas.
- Spots in Jupiter's atmosphere are circulating weather patterns.
- Models indicate that Jupiter has a core of heavy elements and a deep mantle of liquid metallic hydrogen in which the planet's magnetic field is generated.
- The magnetic field around Jupiter traps high-energy particles from the Sun to form intense radiation belts.
- Jupiter must be very hot inside because heat is flowing out of it.
- Jupiter's ring is composed of dark particles that strongly forward-scatter light, which means the particles are very small. They are probably composed of dust resulting from meteorite impacts on Jupiter's moons.
- Jupiter's ring, like all of the rings in the solar system, lies inside the planet's Roche limit, where moons would be torn apart or unable to form.
- Grooves on Ganymede, smooth ice and cracks on Europa, and active volcanoes on Io show that tidal heating has made these moons active.

14.3 Saturn

- Saturn is less dense than water and contains a small core and less metallic hydrogen than Jupiter.
- The cloud layers on Saturn occur at the same temperature as those on Jupiter, but, because Saturn is farther from the Sun and colder, the cloud layers are deeper in the hydrogen atmosphere below a layer of methane haze.
- Saturn's rings are composed of icy particles ranging in size from boulders to dust. In some regions the ice is purer than in other regions.
- Grooves and other features in the rings can be produced by resonances with moons or by waves that propagate through the rings.
- Narrow rings and sharp ring edges can be confined by shepherd satellites.
- The rings are short-lived. They cannot be as old as their planet and must be replenished now and then with material from meteorites and comets colliding with moons.
- Titan has a cold, cloudy nitrogen and methane atmosphere. Sunlight entering Titan's atmosphere can convert methane into complex carbon-rich molecules to form haze and particles that settle out to coat the surface with dark organic goo. Methane lakes may have been detected on Titan's surface in radar images made by the Cassini probe.
- Enceladus has a light surface with some uncratered regions. Geysers of water and ice spray from the south polar region and provide ice particles to the E ring.

14.4 Uranus and Neptune: Ice Giants

- Uranus is much less massive than Jupiter, and its internal pressure cannot produce liquid hydrogen. It has a heavy-element core and a mantle of slushy or solid ice and rock below a hydrogen-rich atmosphere.

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- The atmosphere of Uranus is almost featureless at visual wavelengths with a pale green-blue colour.
- The larger moons of Uranus are icy and heavily cratered, with some signs of past geological activity.
- The rings of Uranus are narrow hoops confined by shepherd satellites. The particles appear to be ice with traces of methane darkened by radiation.
- Uranus rotates "on its side," with its axis nearly in the plane of its orbit, perhaps because of a major impact during its early history.
- Neptune is an ice giant like Uranus with little or no liquid hydrogen in its interior.
- The atmosphere of Neptune, marked by faint patterns of belt–zone circulation, is rich in hydrogen and coloured blue by traces of methane.
- Neptune's satellite system is odd in that Nereid has an extremely elliptical orbit and Triton orbits backwards.
- Triton is icy with a thin atmosphere and frosty polar caps. Smooth areas suggest past geological activity, and dark smudges mark the location of active nitrogen geysers.
- The rings of Neptune are made of dark icy particles in narrow hoops. Neptune's rings contain arcs produced by the gravitational influence of one or more moons.

14.5 Dwarf Planets

- So far, five dwarf planets have been approved by the IAU: Eris, Haumea, Makemake, and Pluto in the Kuiper belt; and Ceres in the asteroid belt between Mars and Jupiter.
- The discovery in 2005 of Eris, about the same size as Pluto, forced the IAU to define planetary bodies, which resulted in the creation of the dwarf planet category. Pluto does not meet all the IAU's criteria to be classified as a planet: though spherical, it hasn't cleared its orbital zone of smaller objects, so it is now considered a dwarf planet.
- Pluto is a small, icy world with five moons, one of which is relatively large. The moons are in orbits highly inclined to Pluto's orbit around the Sun. Pluto has a thin atmosphere.
- Plutinos are other Kuiper belt objects caught in a 3:2 resonance with Neptune.
- Ceres, discovered in 1801, has similar characteristics to the other dwarf planets that have densities less than half that of Earth, compositions of ice and rock, and natural satellites.
- Haumea and Makemake have highly eccentric orbits inclined severely to the ecliptic plane.

KEY TERMS

liquid metallic hydrogen A form of liquid hydrogen that is a good electrical conductor; inferred to exist in the interiors of Jupiter and Saturn. (p. 339)

magnetosphere The volume of space around a planet within which the motion of charged particles is dominated by the planetary magnetic field rather than the solar wind. (p. 340)

belt–zone circulation The atmospheric circulation typical of Jovian planets in which dark belts and bright zones encircle the planet parallel to its equator. (p. 340)

forward scattering The optical property of finely divided particles to preferentially direct light in the original direction of the light's travel. (p. 340)

Roche limit The minimum distance between a planet and its satellite so that the satellite can hold itself together by its own gravity. If a satellite's orbit brings it within its planet's Roche limit, tidal forces will pull the satellite apart. (p. 340)

tidal heating The heating of a planet or satellite because of friction caused by tides. (p. 344)

ovoid The oval features found on Miranda, a satellite of Uranus. (p. 351)

dwarf planet A body that orbits the Sun, is not a satellite of a planet, is massive enough to pull itself into a spherical shape, but is not massive enough to clear out other bodies in and near its orbit—for example, Pluto, Eris, and Ceres. (p. 353)

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Life on Other Worlds

TOPIC SUMMARIES

15.1 The Nature of Life

What is life?

- The process of life extracts energy from the environment, maintains the organism, and modifies the surroundings to promote the organism's survival.
- Living things have a physical basis—the arrangement of matter and energy that makes life possible. Life on Earth is based on carbon chemistry.
- Living things must also have controlling units of information, which can be passed to each new generation.
- Genetic information for life on Earth is stored in long carbon-chain molecules such as DNA.
- The DNA molecule stores information in the form of chemical bases linked together like the rungs of a ladder. Copied by the RNA molecule, the patterns of bases act as recipes for the manufacture of proteins and enzymes that are, respectively, the main structural and control components of the life process.
- When a cell divides, the DNA molecules split lengthwise and duplicate themselves so that each of the new cells can receive a copy of the genetic information.
- Errors in duplication or damage to the DNA molecule can produce mutants, which are organisms that contain new DNA information and have new properties. Variation in genetic codes can become widespread among individuals in a species.
- Natural selection determines which of these variations are best suited to survive, and the species evolves to fit its environment.

15.2 Life in the Universe

How did life originate on Earth?

- The oldest fossils on Earth are at least 3.4 billion years old. These fossils provide evidence that life began in the oceans.
- Fossil evidence indicates that life began on Earth as simple organisms, such as bacteria, and evolved into more complex creatures.
- The Miller-Urey experiment shows that the chemical building blocks of life form naturally under a wide range of circumstances.
- Biologists hypothesize that chemical evolution concentrated simple molecules into a diversity of larger, stable molecules, but those molecules did not reproduce copies of themselves.
- Biological evolution began when molecules started reproducing.
- Not until about 0.5 billion years ago did life forms become large and complex, during the period called the Cambrian explosion.
- Life emerged from the oceans only about 0.4 billion years ago, and human intelligence developed over the last 3 million (0.003 billion) years.

Could life begin on other worlds?

- Life as it is known on Earth requires liquid water and thus a specific range of temperatures.
- No other planet in our solar system appears to harbour life at present. Most are too hot or too cold, although life might have begun on Mars before it became too cold and dry.
- Liquid water exists—and therefore Earth-like life is at least possible—on many of the moons of the giant planets, such as Jupiter's moon Europa and Saturn's moon Enceladus. We are still discovering all the places where liquid water may exist on Jovian moons.
- Because the origin of life and its evolution into intelligent creatures took so long on Earth, scientists do not consider short-lived main-sequence stars such as those of spectral types O, B, and A to be likely hosts for life-bearing planets.
- Main-sequence G and K stars are thought to be likely candidates to host planets with life. The fainter M stars are also possibilities.
- The habitable zone around a star may be larger than scientists had expected, given the wide variety of living things now found in extreme environments on Earth and the possibility of tidal heating of moons orbiting large planets.

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15.3 Intelligent Life in the Universe

Can Earthlings communicate with civilizations on other worlds?

- The large distances between stars make interstellar travel a formidable challenge for any species, whether human or alien.
- Radio communication between solar systems may be possible, but a real conversation would be difficult because, even travelling at the speed of light, the return travel times for radio signals can range from decades to millennia.
- Broadcasting a radio beacon of pulses would distinguish the signal from naturally occurring radio emission and identify the source as a technological civilization. The best part of the radio spectrum for communication is called the water hole, the wavelength range from the 21-cm spectral line of hydrogen to the 18-cm line of OH. Even so, millions of radio wavelengths need to be monitored to fully survey the water hole for a given target star.
- Sophisticated searches are now underway to detect radio transmissions from civilizations on other worlds, but such SETI programs are hampered by limited computer power, limited funding, and radio noise pollution from human civilization.
- The Drake equation can be used to estimate the total number of communicating extraterrestrial civilizations in our galaxy, but many of its parameters are poorly constrained by science.

KEY TERMS

astrobiology The study of the origin and evolution of life on Earth and the possibility of life on other worlds. (p. 360)

biological evolution The processes of mutation, variation, and natural selection by which life adjusts itself to its changing environment. (p. 361)

natural selection The process by which genetic traits that confer advantages to survival or reproduction are preserved, gradually altering organisms to suit their environments. (p. 361)

stromatolite A layered formation caused by mats of algae or bacteria combined with sediments. (p. 361)

DNA (deoxyribonucleic acid) The long carbon-chain molecule that records information to govern the biological activity of the organism. DNA carries the genetic data passed to offspring. (p. 362)

amino acid Carbon-chain molecule that is the building block of protein. (p. 362)

protein Complex molecule composed of amino acid units. (p. 362)

enzyme Special protein that controls processes in an organism. (p. 362)

RNA (ribonucleic acid) Long carbon-chain molecules that use the information stored in DNA to manufacture complex molecules necessary to the organism. (p. 363)

chromosome A body within a living cell that contains genetic information responsible for the determination and transmission of hereditary traits. (p. 363)

gene A unit of DNA—or sometimes RNA—information responsible for controlling an inherited physiological trait. (p. 363)

abiogenesis The process by which life forms from non-living components. (p. 364)

Miller-Urey experiment An experiment that attempted to reproduce early Earth conditions and showed how easily amino acids and other organic compounds can form from non-biological ingredients. (p. 364)

primordial soup The rich solution of organic molecules in Earth's first oceans. (p. 364)

multicellular Comprising more than one cell. (p. 366)

Cambrian explosion A geologically brief period about 540 million years ago during which fossil evidence indicates life on Earth became complex and diverse. (p. 366)

habitable zone A region around a star within which planets have temperatures that permit the sustained existence of liquid water on their surfaces. (p. 371)

SETI The search for extraterrestrial intelligence. (p. 373)

water hole The interval of the radio spectrum between the 21-cm hydrogen emission line and the 18-cm OH emission line; wavelengths likely to be used in the search for extraterrestrial life. (p. 373)

Drake equation The equation that estimates the total number of communicative civilizations in the Milky Way Galaxy. (p. 375)

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Magnitudes

Astronomers use a simple formula to convert between magnitudes and fluxes (brightness). If two stars have fluxes F_A and F_B, then the ratio of their fluxes is F_A/F_B. Magnitude scale is defined so two stars that differ by five magnitudes have a flux ratio of exactly 100. Therefore, two stars that differ by one magnitude must have a flux ratio that equals the fifth root of 100, $\sqrt[5]{100}$ or $100^{0.2}$, which equals 2.51; that is, the light arriving at Earth from one star must be 2.51 times brighter than from the other. Two stars that differ by two magnitudes will have a flux ratio of about 2.51 × 2.51, which is approximately 6.31, and so on (see Table 1).

EXAMPLE A: Suppose star C is seventh magnitude, and star D is tenth magnitude. What is their brightness ratio? That is, what is the ratio of their fluxes?

SOLUTION: The magnitude difference is three magnitudes, and Table 1 shows the corresponding flux ratio is 15.8. Therefore, star C is 15.8 times brighter (has 15.8 times as much flux arriving at Earth) as star D.

A table is convenient, but for more precision you can express the relationship as a simple formula. The flux ratio F_A/F_B is equal to 2.51 raised to the power of the magnitude difference $m_B - m_A$:

$$\frac{F_A}{F_B} = (2.51)^{(m_B - m_A)}$$

In Example A, $(2.51)^{(10-7)} = (2.51)^3 = 15.8$

Table 1 Magnitude Differences and Flux Ratios

Magnitude Difference	Corresponding Flux Ratio
0.00	1.00
1.00	2.51
2.00	6.31
3.00	15.8
4.00	39.8
5.00	100
…	
10.0	10 000
20.0	100 000 000

On the other hand, when you know the flux ratio and want to find the magnitude difference, it is convenient to rearrange the previous formula which now includes the base 10 logarithm of the flux ratio (2.51 is rounded to 2.5).

$$m_B - m_A = 2.5 \log(F_A/F_B)$$

EXAMPLE B: The light from Sirius has 24.2 times as much flux—is 24.2 times brighter—compared to light from Polaris. What is their magnitude difference?

SOLUTION: The magnitude difference is 2.5 times the logarithm of 24.2, which is written 2.5 log(24.2). Your calculator tells you the logarithm of 24.2 is 1.38, so the magnitude difference between Sirius and Polaris is 2.5 × 1.38, which equals 3.46 magnitudes.

Absolute Magnitude and Distance

Apparent visual magnitude tells you how bright a star looks; see the **Magnitudes** Math Reference Card. Absolute visual magnitude, M_V, the apparent visual magnitude the star would have if it were 10 pc away, tells you how luminous the star really is. If you know a star's apparent visual magnitude and its distance, you can calculate its absolute visual magnitude. The magnitude–distance formula that allows this calculation relates apparent visual magnitude, m_V, distance in parsecs, d, and absolute visual magnitude, M_V:

$$m_V - M_V = -5 + 5 \log(d)$$

Sometimes it is convenient to rearrange the equation if you are trying to find the distance:

$$d = 10^{(m_v - M_v + 5)/5}$$

EXAMPLE: The star Polaris is 133 pc from Earth and has an apparent magnitude of 2.0. What is its absolute visual magnitude?

SOLUTION: A calculator tells you that log(133) equals 2.12, so you substitute into the first equation to get

$$2.0 - M_V = -5 + 5(2.12)$$

Solving for M_V tells you that the absolute visual magnitude of Polaris is −3.6. If it were only 10 pc from Earth, it would dominate the night sky.

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Newton's Laws of Motion and Gravitation

Isaac Newton discovered that the motion of an object is related to the forces (push or pull) exerted on the object. For an object of mass m, the acceleration, a, of the object is directly proportional to the net force, F, acting on the object.

$$F = ma$$

EXAMPLE A: How much force is required to increase the speed of a 1500 kg car from rest to 50.0 km/h in 10.0 seconds?

SOLUTION: Note that acceleration is the rate of change of velocity:

$$a = \frac{\Delta v}{\Delta t}$$

Δv is the change in velocity (final velocity minus initial velocity) and Δt is the time interval over which the change took place. In our example Δv = 50.0 km/h = 13.9 m/s and Δt = 50.0s. Therefore,

$$F = ma = m\frac{\Delta v}{\Delta t} = 1500\,\text{kg} \times \frac{13.9\,\text{m/s}}{10.0\,\text{s}} = 2080\,\text{N}$$

NOTE: We need to convert the speed from *km/h* to *metres/second* (m/s) in order to express the force in units of *N* (Newtons), which is the SI unit of force (see Appendix A).

Newton also discovered that all massive objects exert a force of attraction, called a gravitational force, on each other. The force of gravitation between any two objects with mass m_1 and m_2 is directly proportional to the products of the masses and inversely proportional to the square of the distance d between their centres of mass:

$$F_{12} = F_{21} = \frac{Gm_1m_2}{d^2}$$

G is the gravitational constant $G = 6.67 \times 10^{-11}\,\text{Nm}^2/\text{kg}^2$ The gravitational force between two objects is typically very small unless the objects are very massive—such as, for example, planets or stars.

EXAMPLE B: What is the gravitational force between Earth and a 1.0 kg object on the surface of Earth?

SOLUTION: The distance d between the 1.0 kg object and the centre of Earth is the radius of Earth. Thus,

$$F_{12} = F_{21} = \frac{Gm_1m_2}{r^2}$$

$$= \frac{(6.67 \times 10^{-11}\,\text{Nm}^2/\text{kg}^2)(M_{\text{Earth}})(1.0\,\text{kg})}{(R_{\text{Earth}})^2} = 9.8\,\text{N}$$

Note that we can also find the acceleration of the 1 kg object using the equation $F = ma$:

$$a = \frac{F}{m} = \frac{9.8\,\text{N}}{1.0\,\text{kg}} = 9.8\,\text{m/s}^2$$

This is, indeed, the acceleration due to Earth's gravity of all objects close to the surface of Earth.

NOTE: The gravitational force is inversely proportional to the square of the distance between the two objects. For example, it decreases by a factor of 4 when the distance is doubled.

Circular Velocity

Circular velocity is the velocity a satellite must have to remain in a circular orbit around a larger body. If the mass of the satellite is small compared that of the central body, the circular velocity is given by

$$V_c = \sqrt{\frac{GM}{r}}$$

In this formula, M is the mass of the central body in kilograms, r is the radius of the orbit in metres, and G is the gravitational constant, $6.67 \times 10^{-11}\,\text{m}^3/\text{s}^2\,\text{kg}$. This formula is all you need to calculate how fast an object must travel to stay in a circular orbit.

EXAMPLE: How fast does the Moon travel in its orbit? The mass of Earth is 5.98×10^{24} kg, and the Moon orbits 3.84×10^8 m from Earth's centre.

SOLUTION: The Moon's velocity is

$$V_c = \sqrt{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{3.84 \times 10^8}} = 1020\,\text{m/s}$$

This calculation shows that the Moon travels 1.02 km along its orbit each second. This value is an average value because the Moon's orbit around Earth is not quite circular.

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The Small-Angle Formula

Figure 1 shows the relationship among the linear diameter, angular diameter, and distance of an object, in this case the Moon. Linear diameter is simply the distance between an object's opposite sides. The average linear diameter of the Moon is 3470 km. The angular diameter of an object is the angle formed by lines extending toward you from opposite edges of the object, meeting at your eye. The farther away a given object is, the smaller its angular diameter.

To find the angular diameter of the Moon, you need to use the small-angle formula. It allows you to calculate the angular diameter of any object.

In the small-angle formula, you must always use the same units for distance and linear diameter. The version of the formula shown here has arc seconds as the unit of angular diameter.* You can use this formula to find any one of the three quantities involved (linear diameter, angular diameter, distance) if you know the other two, by cross-multiplying.

$$\frac{\text{angular diameter (in arc seconds)}}{2.06 \times 10^5} = \frac{\text{linear diameter}}{\text{distance}}$$

EXAMPLE: The Moon's linear diameter is 3470 km, and its average distance from Earth is 384 000 km. What is its angular diameter?

SOLUTION: Because the Moon's linear diameter and distance are both given in the same units, kilometres, you can put them directly into the small-angle formula:

$$\frac{\text{angular diameter}}{2.06 \times 10^5} = \frac{3470\,\text{km}}{384\,000\,\text{km}}$$

The resulting angular diameter is 1.86×10^3 arc seconds to three digits' precision, which equals 31 arc minutes—about 0.5°.

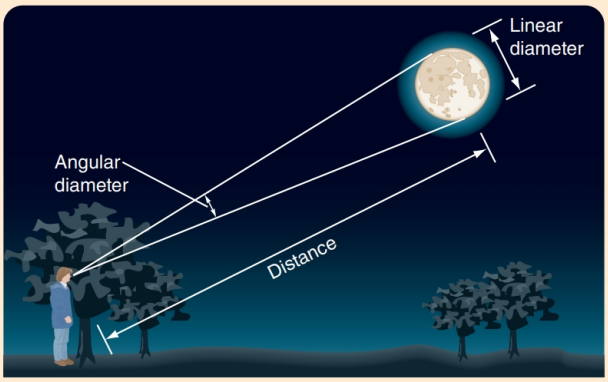


Figure 1 The three quantities related by the small-angle formula.

*When you divide by 2.06 × 105, you convert the angle from arc seconds into radians.

Wave Properties

When a wave travels through a medium, it is characterized by three properties. A wave is just a series of peaks and valleys (or ups and downs) and is one of two types, transverse or longitudinal. A transverse wave is when the particles being affected by the wave move perpendicularly to the direction in which the wave is moving (e.g., light); a longitudinal wave is when the particles move back and forth in the same direction in which the wave is moving (e.g., sound). The distance from one peak to the next peak (or valley to the next valley) is called the wavelength, usually denoted by λ, measured in metres. The number of waves passing any point in space is known as the frequency, f, measured in cycles/second. Finally, as the wave moves through the medium (air, glass, vacuum, etc.) it is characterized by its speed, v, measured in metres/second.

These quantities have a simple relationship:

$$v = f\lambda, \qquad \text{or} \qquad \lambda = v/f$$

Furthermore, if the wave phenomenon is light, then the energy, E, of a photon of light is proportional to the wavelength of the light, sometimes known as the Planck–Einstein relation:

$$E = hf$$

where h is Planck's constant, 6.626×10^{-34} joule seconds.

EXAMPLE A: Consider a sound wave travelling in air. The speed of the wave in air is 343.2 m/s and is independent of the frequency (pitch) of the sound. (This value is somewhat dependent on the air temperature so we have quoted a value for 20°C.) What is the wavelength of middle C on the piano, $f = 261.2$ Hz (cycles/second)?

SOLUTION: $\lambda = \dfrac{v}{f} = \dfrac{343.2}{261.2} = 1.3\,\text{m (metres)}$

EXAMPLE B: For light travelling through interstellar space the speed is 300 000 km/s or 3×10^8 m/s, usually denoted by c. Again, this speed is the same for all light whether it is visible light, X-rays, or radio waves. What is the frequency of H_α light (the red line in the Hydrogen Balmer series; see **Visualizing Astronomy 5.1, Atomic Spectra**) whose wavelength is 656.3 nm (nanometres)?

SOLUTION: $f = \dfrac{c}{\lambda} = \dfrac{3 \times 10^8}{656.3 \times 10^{-9}} = 4.6 \times 10^4\,\text{cycles/s}$

$= 457\,\text{THz}$

What is the energy of a photon of this frequency?

$$E = hf = (6.626 \times 10^{-34}) \times (4.6 \times 10^{14})$$
$$= 3.05 \times 10^{-19}\,\text{joules}$$

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The Powers of a Telescope

The light-gathering power (*LGP*) of a telescope is proportional to the area of the primary mirror or lens. A primary with a large area gathers a large amount of light. The area of a circular lens or mirror of diameter D is $\pi(D/2)^2$. To compare the relative *LGP* of two telescopes A and B, you can calculate the ratio of the areas of their primaries, which is the ratio of the diameters (D) squared:

$$\frac{LGP_A}{LGP_B} = \left(\frac{D_A}{D_B}\right)^2$$

EXAMPLE A: Suppose you compare a 4-cm telescope with a 24-cm telescope. How much more light will the larger telescope gather?

SOLUTION:

$$\frac{LGP_{24}}{LGP_4} = \left(\frac{24}{4}\right)^2 = 6^2 = 36 \text{ times more light}$$

EXAMPLE B: Your dark-adapted eye acts like a telescope with a diameter of about 0.8 cm, the maximum diameter of the pupil. How much more light can you gather if you use a 24-cm telescope, relative to your unaided eye?

SOLUTION:

$$\frac{LGP_{24}}{LGP_{eye}} = \left(\frac{24}{0.8}\right)^2 = 30^2 = 900 \text{ times more light}$$

The resolving power of a telescope is the angular distance between two stars that are just barely visible through the telescope as separate images. The resolving power α in arc seconds of a telescope with diameter D in metres and that is collecting light of wavelength λ in metres equals:

$$\alpha = 2.06 \times 10^5 \left(\frac{\lambda}{D}\right) \text{ arc seconds}$$

The multiplication factor of 2.06×10^5 is the conversion between radians and arc seconds (refer to **The Small-Angle Formula** Math Reference Card).

If the wavelength of light being studied is assumed to be 550 nm, in the middle of the visual band, then the above formula simplifies to

$$\alpha = \frac{0.113}{D} \text{ arc seconds}$$

EXAMPLE C: What is the resolving power of a 10-cm-diameter (=0.10 m) telescope observing at visual wavelengths?

SOLUTION:

$$\alpha = 2.06 \times 10^5 \left(\frac{550 \times 10^{-9}}{0.10}\right) = 1.13 \text{ arc seconds}$$

or, equivalently,

$$\alpha = \frac{0.113}{0.10} = 1.13 \text{ arc seconds}$$

In other words, using a 10-cm-diameter telescope, if the lenses are of good quality, and if the seeing is good, you should be able to distinguish as separate points of light any pair of stars farther apart than about 1.1 arc seconds. Stars any closer together than that would be blurred together into a single image by the diffraction fringes.

The same formula can be applied to a radio telescope.

EXAMPLE D: What is the resolving power of a radio telescope with a dish (primary mirror) diameter of 100 m observing at a wavelength of 21 cm (0.21 m)?

SOLUTION:

$$\alpha = 2.06 \times 10^5 \left(\frac{0.21}{100}\right) = 430 \text{ arc seconds}$$

Note how poor the resolution of even a large radio dish is compared with optical telescopes. That resolution limit of 430 arc seconds corresponds to 1/4 the diameter of the full moon.

The magnification power M of a telescope is the ratio of the focal length of the primary lens or mirror F_p divided by the focal length of the eyepiece F_e:

$$M = \left(\frac{F_p}{F_e}\right)$$

EXAMPLE E: What is the magnification of a telescope with a primary mirror focal length of 80 cm if it is used with an eyepiece with a focal length of 0.50 cm?

SOLUTION: The magnification is 80 divided by 0.50, or 160 times.

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Blackbody Radiation

Blackbody radiation is described by two simple laws that can be expressed in precise mathematical form. So many objects give off radiation as blackbodies that these two laws are important principles in the analysis of light from the universe.

Wien's law expresses quantitatively the relation between temperature and the wavelength at which a blackbody radiates the most energy: its wavelength of maximum intensity (λ_{max}). Written for conventional intensity units, the law is expressed as follows:

$$\lambda_{max} = \frac{2.90 \times 10^6}{T}$$

That is, the wavelength in nanometres of maximum radiation intensity emitted by a blackbody is inversely proportional to the blackbody's temperature on the Kelvin scale. This law is a powerful aid in astronomy.

EXAMPLE: A cool star has a surface temperature of 2900 K. At what wavelength is its radiation most intense?

SOLUTION: Using Wein's law, we have

$$\lambda_{max} = \frac{2.90 \times 10^6}{T} = 2.90 \times 10^6 / 2900 = 1000 \text{ nm}$$

which is in the near-infrared part of the spectrum. In contrast, a very hot star, with a temperature of 29 000 K, ten times as hot, radiates most intensely at a wavelength of 100 nm, which is in the ultraviolet.

The Stefan–Boltzmann law, named after the two scientists who discovered it, relates the temperature of a blackbody to the total radiated energy. Recall that energy is expressed in units called joules (symbolized by capital J). The total radiation in units of joules per second given off by one square metre of the surface of the object equals a constant number, represented by sigma (σ), multiplied by the temperature raised to the fourth power:*

$$E = \sigma T^4 \text{ (J/s/m}^2\text{)}$$

How does this help you understand stars? Suppose a star the same size as the Sun has a surface temperature twice as hot as the Sun's surface. Then each square metre of that star radiates not just twice as much energy, but 2^4, or 16, times as much energy. From this law you can see that a small difference in temperature between two stars can produce a very large difference in the amount of energy emitted from the stars' surfaces.

*For the sake of completeness, you can note that the constant σ equals 5.67×10^{-8} J/(s m^2 K^4) (units of joules per second per square metre per degree Kelvin to the fourth power).

The Doppler Formula

Astronomers can measure radial velocity by using the Doppler effect. The "laboratory" wavelength λ_0 is the wavelength a certain spectral line would have if the source of the light is not moving relative to the spectrograph. In the spectrum of a star, this spectral line is shifted by some small amount, $\Delta\lambda$. If the wavelength is increased (a red shift), $\Delta\lambda$ is positive; if the wavelength is decreased (a blue shift), $\Delta\lambda$ is negative. The radial velocity, V_r, of the star is given by the Doppler formula:

$$\frac{V_r}{C} = \frac{\Delta\lambda}{\lambda_0}$$

That is, the radial velocity divided by the speed of light, c, is equal to $\Delta\lambda$ divided by λ_0. In astronomy, radial velocities are almost always given in kilometres per second, so c is expressed as 300 000 km/s.

EXAMPLE: If the laboratory wavelength of a certain spectral line is 600.00 nm, and the line is observed in a star's spectrum at a wavelength of 600.10 nm, what is the radial velocity of the star?

SOLUTION: Clearly, $\Delta\lambda$ is +0.10 nm, and the radial velocity is given by

$$V_r = \left(\frac{\Delta\lambda}{\lambda_0}\right) c = (0.10/600)\, c = 50 \text{ km/s}$$

Because $\Delta\lambda$ is positive, you know the star is receding from you. The ratio of V_r/c is called "redshift" z and is used in Hubble law to determine the distance to the object.

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Hydrogen Fusion

When four hydrogen nuclei fuse to make one helium nucleus, a small amount of matter seems to disappear. To see this, subtract the mass of a helium nucleus from the mass of four hydrogen nuclei:

$$\begin{aligned} 4 \text{ hydrogen nuclei} &= 6.690 \times 10^{-27}\,\text{kg} \\ -1 \text{ helium nucleus} &= 6.646 \times 10^{-27}\,\text{kg} \\ \hline \text{Difference in mass} &= 0.044 \times 10^{-27}\,\text{kg} \end{aligned}$$

That mass difference, 0.044×10^{-27} kg, does not actually disappear but is converted to energy according to Einstein's famous equation:

$$\begin{aligned} E &= mc^2 \\ &= (0.044 \times 10^{-27}\,\text{kg}) \times (3.0 \times 10^{8}\,\text{m/s})^2 \\ &= 4.0 \times 10^{-11}\,\text{J} \end{aligned}$$

Recall that 1 joule is approximately equal to the energy of motion of an apple falling from a table to the floor.

The Mass–Luminosity Relation

You can estimate the luminosity of a main-sequence star based on the star's mass using a simple equation. A main-sequence star's luminosity in terms of the Sun's luminosity equals its mass in solar masses raised to the 3.5 power:

$$L = M^{3.5}$$

This is the mathematical form of the mass–luminosity relation. It is only an approximation, as shown by the red line in Figure 6.16, but it applies to most main-sequence stars over a wide range of stellar masses.

EXAMPLE: What is the luminosity of a main-sequence star with four times the mass of the Sun?

SOLUTION: The star is about 128 times more luminous than the Sun because

$$L = M^{3.5} = 4^{3.5} = 128$$

Parallax and Distance

To find the distance to a star from its measured parallax, astronomers use the same calculation, as described in **The Small-Angle Formula** Math Reference Card. Imagine that you observe our solar system from the star. Figure 6.2 shows that the angular separation you would measure between the Sun and Earth equals the star's parallax, p. Recall that the small-angle formula relates an object's angular diameter, its linear diameter, and its distance. In this case, the angular diameter is the parallax angle p, and the linear diameter, the base of the triangle, is 1 AU. With the small-angle formula rearranged slightly, the distance, d, to the star in AU is equal to 2.06×10^5 divided by the parallax in arc seconds:

$$d = \frac{2.06 \times 10^5}{p}$$

The constant in the numerator is a conversion factor: the number of arc seconds in a radian.

Because the parallaxes of even the nearest stars are less than 1 arc second, the distances in AU are inconveniently large numbers. To keep the numbers manageable, astronomers have defined the parsec as their primary unit of distance in a way that simplifies the arithmetic. One parsec equals 2.06×10^5 AU, so the equation becomes

$$d = \frac{1}{p}$$

Thus, a parsec is the distance to an imaginary star whose parallax is 1 arc second.

EXAMPLE: The star Altair has a parallax of 0.194 arc second. How far away is it?

SOLUTION: The distance in parsecs (pc) equals 1 divided by 0.194, or 5.16 pc:

$$d = \frac{1}{0.194} = 5.16\,\text{pc}$$

One parsec equals about 3.26 light-years(ly), so Altair is 16.8 ly away.

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The Life Expectancies of Stars

You can estimate the amount of time a star spends on the main sequence—its life expectancy, τ—by estimating the amount of fuel it has and dividing by the rate at which it consumes that fuel:

$$\tau = \frac{\text{fuel supply}}{\text{rate of consumption}}$$

The amount of fuel a star has is proportional to its mass, M, and the rate at which it uses up its fuel is proportional to its luminosity, L. Thus, its life expectancy must be proportional to M/L. You can simplify this equation further because the luminosity of a star depends on its mass raised to the 3.5 power ($L = M^{3.5}$); see **The Mass–Luminosity Relation** Math Reference Card. So the life expectancy is

$$\tau = \frac{M}{M^{3.5}} = \frac{1}{M^{2.5}}$$

If you express the mass in solar masses, the lifetime will be in solar lifetimes.

EXAMPLE: How long can a 4-solar-mass star live?

SOLUTION:

$$\tau = \frac{1}{4^{2.5}} = \frac{1}{32} \text{ solar lifetimes}$$

Solar models show that the Sun, presently 5 billion years old, will last another 5 billion years. So a solar lifetime is approximately 10 billion years, and a 4-solar-mass star will last for about

$$\tau = \frac{1}{32} \times (10 \times 10^9 \text{ yr}) = 310 \times 10^6 \text{ years}$$

Luminosity, Radius, and Temperature

The luminosity, L, of a star depends on two things: its size and its temperature. Recall from the **Blackbody Radiation** Math Reference Card that the amount of energy emitted per second from each square metre of the star's surface is σT^4. Therefore, the star's luminosity can be written as its surface area in square metres times the amount it radiates from each square metre:

$$L = (\text{surface area}) \times \sigma T^4$$

Because a star is a sphere, you can use the formula for surface area, $4\pi R^2$. Then the luminosity is

$$L = 4\pi R^2 \sigma T^4$$

If you express luminosity, radius, and temperature in proportion to the Sun, you get a simpler form*:

$$\frac{L}{L_\odot} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{T}{T_\odot}\right)^4$$

EXAMPLE A: How luminous is a star that has 10 times the Sun's radius but only half the temperature?

SOLUTION:

$$\frac{L}{L_\odot} = \left(\frac{10}{1}\right)^2 \left(\frac{1}{2}\right)^4 = \frac{100}{1} \times \frac{1}{16} = 6.25$$

This star is 6.25 more luminous than the Sun. You can also use this formula to find sizes of stars.

EXAMPLE B: What is the radius (relative to the Sun's radius) of a star whose absolute magnitude is 11 and whose spectrum shows it has twice the Sun's temperature?

SOLUTION: The star's absolute magnitude is four magnitudes brighter than the Sun. Recall from the **Magnitudes** Math Reference Card that four magnitudes is approximately a factor of 2.51^4, or about 40. The star's luminosity is therefore about 40 $L_\odot$. With the luminosity and temperature, you can find the radius:

$$\frac{40}{1} = \left(\frac{R}{R_\odot}\right)^2 \left(\frac{2}{1}\right)^4$$

Solving for the radius, you get the following:

$$\left(\frac{R}{R_\odot}\right)^2 = \frac{40}{2^4} = \frac{40}{16} = 2.5$$

So the radius is

$$\frac{R}{R_\odot} = \sqrt{2.5} = 1.58$$

The star is 58 percent larger in radius than the Sun.

*In astronomy, the symbols $\odot$ and $\oplus$ refer, respectively, to the Sun and Earth. Thus $L_\odot$ refers to the luminosity of the Sun, $T_\odot$ refers to the temperature of the Sun, and so on.

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The Masses of Binary Stars

Johannes Kepler's third law of orbital motion worked only for the planets in our solar system. When Newton realized that mass produces the gravitational attraction that governs orbits, he made that law into a general principle. Newton's version of Kepler's third law applies to any pair of objects that orbit each other. The total mass of the two objects is related to the average distance, a, between them and their orbital period, P. If the masses are M_A and M_B, then

$$M_A + M_B = \frac{a^3}{p^2}$$

In this formula, a is expressed in AU, P in years, and the mass in solar masses.

Notice how this formula is related to Kepler's third law of planetary motion (refer to Table 3.1). Almost all the mass of the solar system is in the Sun. If you apply this formula to any planet in our solar system, the total mass is 1 solar mass. Then the formula becomes $P^2 = a^3$, which is Kepler's third law.

This formula lets you find the masses of binary stars. You must know the distance to the binary system to be able to convert the average angular separation between the two stars into AU. Using that and their orbital period in years, the sum of the masses of the two stars in solar units is just a^3/P^2.

EXAMPLE A: If you observe a binary system with a period of 32 years and an average separation of 16 AU, what is the total mass?

SOLUTION: The total mass equals $16^3/32^2$, which equals 4 solar masses.

EXAMPLE B: Let's call the two stars in the previous example A and B. Suppose star A is 12 AU away from the centre of mass, and star B is 4 AU away. What are the individual masses?

SOLUTION: The ratio of the masses must be 12:4, which equals a ratio of 3:1. What two numbers add up to 4 and have the ratio 3:1? Star B must be 3 solar masses, and star A must be 1 solar mass.

The Hubble Law

The apparent velocity of recession of a galaxy, V_r, in kilometres per second is equal to the Hubble constant, H_0, multiplied by the distance to the galaxy, d, in megaparsecs:

$$V_r = H_0 d$$

Astronomers use this equation as a way to estimate distance from a galaxy's apparent velocity of recession. Redshift $z = V_r/c$ is used in Hubble law to determine the distance to the object (refer to **The Doppler Formula** in the Math Reference Cards). Astronomers often refer to the distance to the object as "redshift."

EXAMPLE: If a galaxy has a radial velocity of 700 km/s, and H_0 is 70 km/s/Mpc,* then the distance to the galaxy equals the velocity divided by the Hubble constant, which is

$$d = \frac{(700\,\text{km/s})}{(70\,\text{km/s/Mpc})} = 10\,\text{Mpc}$$

Notice how the units in km/s cancel out to leave the distance in Mpc.

*H_0 has the units of a velocity divided by a distance. These are usually written as km/s/Mpc, meaning km/s per Mpc.

The Age of the Universe

Dividing the distance to a galaxy by the apparent velocity with which it recedes gives you an estimate of the age of the universe, and the Hubble constant simplifies your task further. The Hubble constant H_0 has the units km/s per Mpc, which is a velocity divided by a distance. If you calculate $1/H_0$, you have a distance divided by velocity. To finish the division and get an age, you need to convert megaparsecs into kilometres, and then the distances will cancel out and leave you with the age in seconds. To get years, divide by the number of units. Then the age of the universe in years is approximately 10^{12} divided by H_0 in its normal astronomical units, km/s/Mpc:

$$\tau_H = \frac{10^{12}}{H_0}\ \text{years}$$

This estimate of the age of the universe is known as the Hubble time. For example, if H_0 is 70 km/s/Mpc, an estimated age for the universe is $10^{12}/70$, or 14 billion, years.

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